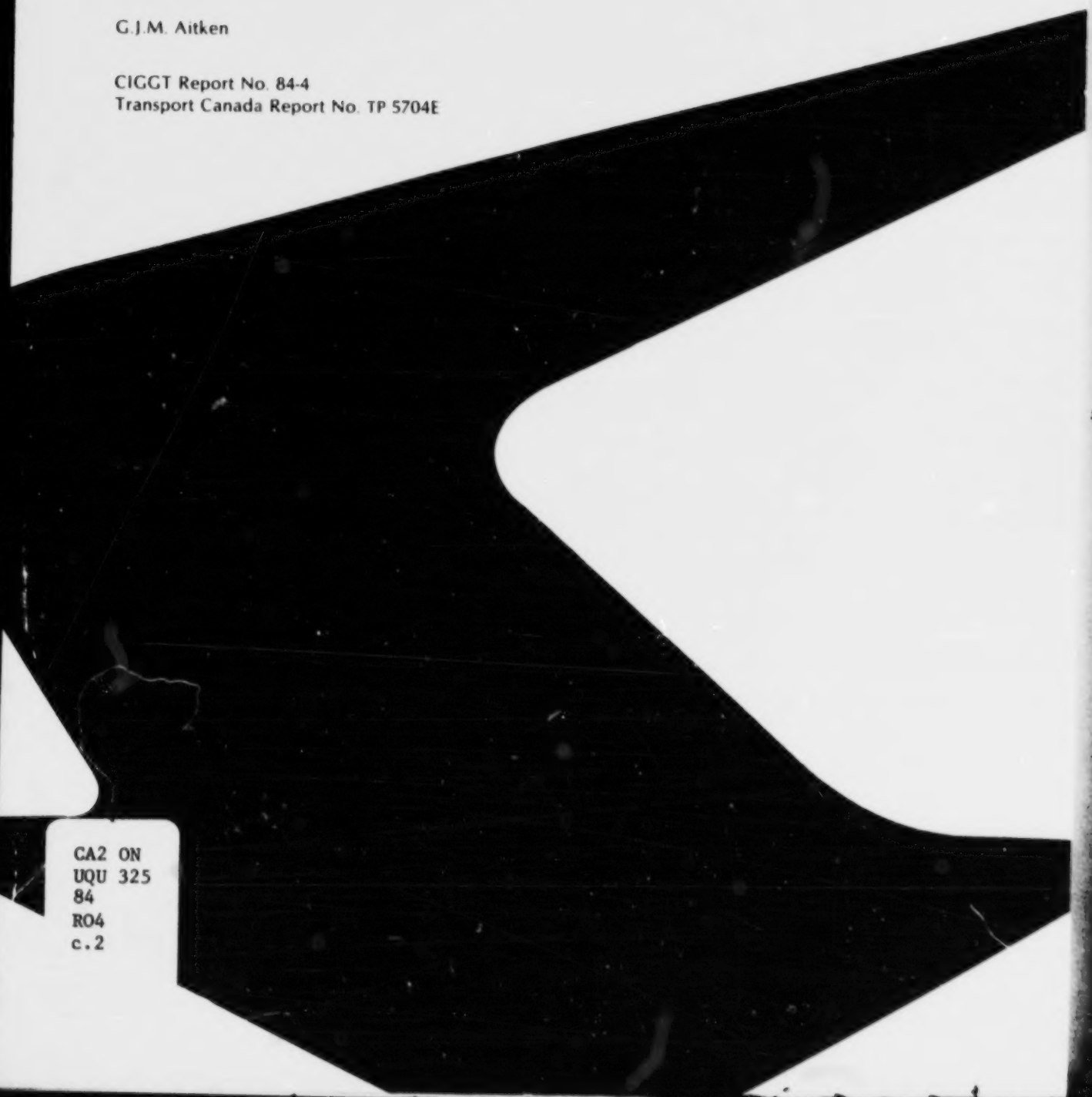
Canadian Institute of
Guided Ground Transport
Queen's University
at Kingston, Ontario

G.J.M. Aitken

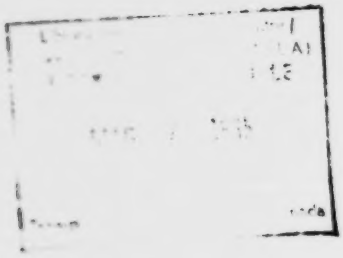
CIGGT Report No. 84-4
Transport Canada Report No. TP 5704E



CA2 ON
UQU 325
84
R04
c.2

CIGGT Project No. PRO-136

CIGGT Report No. 84-4
Transport Canada Report No. TP-5704E



# REVIEW OF SIGNAL AND POWER TRANSMISSION TECHNOLOGY FOR FREIGHT TRAINS

prepared for

Transportation Development Centre, Transport Canada

by

G.J.M. Aitken
Department of Electrical Engineering
Queen's University at Kingston

Canadian Institute of Guided Ground Transport
Queen's University at Kingston, Ontario
K7L 3N6

July 1984

## ACKNOWLEDGEMENTS

The author wishes to thank the many individuals, companies and agencies who provided information and advice on the topics of this study. Of special note were the contributions of S. Riddell, Pyle-National; T. Thornton, AMP Corp.; and R.J. Pomeroy, Glenayre Electronics. Valuable assistance was received from I. Henry and J. Taylor, Toronto Transit Commission; J.B. Hopkins, U.S. Department of Transportation; C. Wright, WABCO; Ms Donnolly, CN Library; Sheila Johnson, Douglas Library, Queen's University; and the personnel of UTDC. The author is grateful for the excellent support provided by Jane Law and Janice Bélanger, CIGGT Librarians, for whom no document or report was too obscure or too remote to obtain. Special thanks to Sherrill Arnold for her participation in the preparation of this report.

ISBN 0-88911-221-5

This report resulted from research conducted through the Canadian Institute of Guided Ground Transport. The report represents the views of the author and does not necessarily have the endorsement of the University or the other participating organizations.

## REPORT DOCUMENTATION FORM

| 1. Transport Canada Report No. | 2. TDC Project No. | 3. Recipient's Catalogue No. |
|---|---|---|
| TP-5704E | 6053 | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| REVIEW OF SIGNAL AND POWER TRANSMISSION TECHNOLOGY FOR FREIGHT TRAINS | July 1984 |
| | 6. Performing Organization Report No. 84-4 |
| 7. Author(s) G.J.M. Aitken | 8. Transport Canada File No. D1465-158-6 |
| 9. Performing Organization Name and Address<br>Canadian Institute of Guided Ground Transport (CIGGT)<br>c/o Queen's University<br>Kingston, Ontario K7L 3N6 | 10. DSS File No. 11SD.T8200-3-3527 |
| | 11. DSS or Transport Canada Contract No. OSD83-00070 |
| 12. Sponsoring Agency Name and Address<br>Transportation Development Centre, Suite 2421<br>1000 Sherbrooke St.W., Montreal, Quebec H3A 2R3<br>Canadian Pacific Ltd, Windsor Station<br>Montreal, Quebec H3C 3E4 | 13. Type of Report and Period Covered Final, Aug./83-July/84 |
| | 14. Sponsoring Agency Code TDC 6053; CP 1871-Q-19 |
| 15. Supplementary Notes | 16. TDC Project Officer M. Anvi |

17. Abstract

A data model and the power requirements for freight train monitoring and brake control are established as a framework for technology assessment. Transmission systems employing on-board and external transmission media are examined. Conventional two-conductor transmission lines have much to offer in simplicity, ruggedness and reliability. Consequently, their weak point, the inter-car connector, has been examined in some detail. No connectors were found which fully met a set of requirements defining the ideal connector; however, a number of potentially useful connector techniques were identified in other applications and warrant further consideration. Fibre optics have promise as an interference-free communications medium if combined with an electric line for power transmission. Four schemes employing radio were examined. Of these, only a system based on a transponder at each car warrants further development.

| 18. Key Words | 19. Distribution Statement |
|---|---|
| Signal transmission;<br>Power transmission;<br>Freight trains | Available on request from CIGGT |

| 20. Security Classification (of this report) | 21. Security Classification (of this page) | 22. No. of Pages | 23. Price |
|---|---|---|---|
| unclassified | unclassified | 119 | |

TDC CDT 79 005

## FORMULE DE DOCUMENTATION POUR RAPPORT

| 1 N° du rapport Transports Canada | 2 N° de l'étude — CDT | 3 N° de catalogue du destinataire |
|---|---|---|
| TP5704E | 6053 | |

| 4 Titre et sous-titre | 5 Date du rapport |
|---|---|
| REVIEW OF SIGNAL AND POWER TRANSMISSION TECHNOLOGY FOR FREIGHT TRAINS | Juillet 1984 |
| | 6 N° du rapport de l'organisme exécutant: 84-4 |
| 7 Auteur(s): G.J.M. Aitken | 8 N° de dossier Transports Canada: D1465-158-6 |
| 9 Nom et adresse de l'organisme exécutant: Canadian Institute of Guided Ground Transport (CIGGT) a/s Queen's University Kingston, Ontario K7L 3N6 | 10 N° de dossier — ASC: 11SD.T8200-3-3527 |
| | 11 N° de contrat — ASC ou Transports Canada: OSD83-00070 |
| 12 Nom et adresse de l'organisme parrain: Centre de développement des transports, Suite 2421 1000 Sherbrooke ouest, Montréal, Québec H3A 2R3 Canadian Pacific Ltd, Gare Windsor Montréal, Québec H3C 3E4 | 13 Genre de rapport et période visée: Final, août 83-juillet 84 |
| | 14 Code de l'organisme parrain: CDT 6053; CP 1871-Q-19 |
| 15 Remarques additionnelles | 16 Agent de projet — CDT: M. Avni |

17 Resumé

Ce rapport concerne l'élaboration d'un modèle de simulation d'une ligne de transmission devant écouler les signaux de surveillance et de freinage dans le cas des trains de marchandises, et la définition des sources d'alimentation à prévoir, délimitant ainsi le cadre d'évaluation des technologies étudiées. Des systèmes de transmission faisant appel soit à des agents matériels embarqués, soit à des agents extérieurs, immatériels ont été envisagés. Il a été constaté que les lignes de transmission bifilaires classiques ont pour elles la simplicité, la robustesse et la fiabilité. C'est pourquoi la recherche a surtout porté sur le point faible des liaisons inter-wagons, c'est-à-dire les connecteurs. Aucune technologie n'a pu satisfaire pleinement à l'ensemble des prescriptions définissant un connecteur parfait. Néanmoins, certaines techniques d'interconnexion utilisées dans des domaines autres que ferroviaires ont été jugées intéressantes. Par exemple, la technologie de fibres optiques qui est insensible aux parasites électromagnétiques, mais qui doit être combinée à une ligne de transmission d'énergie électrique. Quatre technologies utilisant la propagation des ondes radio ont été examinées. Seule celle qui utilise un transpondeur à bord des wagons mériterait d'être approfondie.

| 18 Mots-clés | 19 Diffusion |
|---|---|
| Transmission de signaux. Transmission d'énergie électrique. Trains de marchandises. | Adresser les demandes au CIGGT |

| 20 Classification de sécurité (de ce rapport) | 21 Classification de sécurité (de cette page) | 22 Nombre de pages | 23 Prix |
|---|---|---|---|
| non-classifié | non-classifiée | 117 | - |

CDT/TDC 79-005

TABLE OF CONTENTS


1. BACKGROUND . . . . . 1

2. OBJECTIVE . . . . . 4

3. STATUS . . . . . 4

4. INVESTIGATIVE PROCEDURE . . . . . 4

5. NEW TECHNOLOGY . . . . . 6

6. GENERAL REQUIREMENTS . . . . . 6
   6.1 Communications Mode . . . . . 6
   6.2 Data Specifications . . . . . 8
      6.2.1 Car-to-Cab Communications . . . . . 8
      6.2.2 Cab-to-Car Communications . . . . . 10
      6.2.3 Cab-to-Cab, Cab-to-Caboose Communications . . . . 11
      6.2.4 Link Length . . . . . 11
      6.2.5 Data Rates and Bandwidths . . . . . 12
   6.3 Noise and Error Rates . . . . . 13
   6.4 Power Requirements . . . . . 14
   6.5 Safety and Fail-Safe Operation . . . . . 15
   6.6 Attenuation and Power Distribution . . . . . 16
   6.7 Other Systems . . . . . 19
   6.8 Subdivision of Systems . . . . . 21

7. ON-BOARD TRANSMISSION MEDIA . . . . . 22
   7.1 Transmission Lines . . . . . 22
      7.1.1 Advantages and Disadvantages . . . . . 22
      7.1.2 Connector Requirements . . . . . 26
      7.1.3 Reliability, Failure Rates and MTBF . . . . . 28
      7.1.4 Causes of Connector Failures . . . . . 31
      7.1.5 Connector Coupling Mechanisms . . . . . 33
      7.1.6 Contact Technology . . . . . 38
      7.1.7 Hermaphroditic Requirement . . . . . 49
      7.1.8 Electromagnetic Interference . . . . . 53
      7.1.9 Forces and Vibration . . . . . 55
      7.1.10 C-Line Connectors . . . . . 56
      7.1.11 Other Aspects . . . . . 59
      7.1.12 Maintenance and Repair . . . . . 59
      7.1.13 Summary . . . . . 60
   7.2 Fibre Optics . . . . . 63
   7.3 Waveguides . . . . . 76

8. COMMUNICATIONS THROUGH EXTERNAL MEDIA . . . . . 79
   8.1 Radio . . . . . 80
   8.2 Inductive Coupling to Wayside Lines . . . . . 84
   8.3 Radiating or Leaky Cables . . . . . 86
   8.4 Transponder Link . . . . . 93

9. ASSESSMENT AND CONCLUSIONS . . . . . 97
9.1 Power and Data Requirements . . . . . 99
9.2 Transmission Lines and Connectors . . . . . 102
9.3 Optical Fibres . . . . . 105
9.4 Waveguide . . . . . 106
9.5 Radio, Inductive Coupling and Leaky Coaxial Cable . . . 106
9.6 Transponder Link . . . . . 107
9.7 Summary of Conclusions . . . . . 107

10. RECOMMENDATIONS . . . . . 109

REFERENCES. . . . . 112

## LIST OF TABLES

8.1 Radiating Cable Characteristics . . . . . 89

9.1 Freight Train Transmission Technology: Summary Assessment . 100

## LIST OF FIGURES

7.1 Two examples of latching lids . . . . . 34
7.2 The Pyle-National C-Line connector for marine and harsh environments . . . . . 35
7.3 An air-electric connector based on the conventional glad-hand air-hose connector . . . . . 37
7.4 Change in contact resistance on remating as a function of exposure time for three platings . . . . . 41
7.5 The socket closing technique used in the C-Line connector . 43
7.6 The closed-entry socket of the type used in the VE Transportation Series by Cannon ITT . . . . . 44
7.7 An example of the butt-contact mechanism . . . . . 46
7.8 Hermaphroditic contact by Anderson Power Products . . . . . 47
7.9 Principle of the hermaphroditic connector shell and end view of the configuration used in the hermaphroditic coaxial connectors by General Radio . . . . . 50
7.10 Tandem connectors . . . . . 52
7.11 Cross-sections of optical fibres . . . . . 64
7.12 Construction of a practical optical-fibre cable . . . . . 66
7.13 The expanded-beam-lens principle in optical-fibre connectors . . . . . 70
7.14 The AEG Telefunken and Fabeg optical communications link being tested on the Berlin subway . . . . . 72
7.15 Essential elements of the optical "contact" . . . . . 72

8.1 A schematic representation of on-board communications by means of independent, cab-to-car radio links . . . . 81
8.2 A schematic representation of cab-to-car communications through inductive coupling to a transmission line . . . 85
8.3 Four radiating coaxial cable structures . . . . . 88
8.4 A schematic representation of cab-to-car communications through radio-frequency coupling to a radiating or leaky coaxial cable . . . . . 88
8.5 A schematic representation of on-board communications by means of a series of transponders . . . . . 94

## 1. BACKGROUND

Major improvements in freight train safety and operating efficiency could be realized if communication links existed between the locomotive cab and the individual cars. Cab-car links would permit:

( i) continuous monitoring of the mechanical state of the cars,

( ii) on-board identification and warning of hazardous conditions, and

(iii) the electrical control of pneumatic brakes,

none of which are current freight train practice. Monitoring and hazard warning could, in many cases, increase freight train safety and reduce maintenance costs by providing early identification of component deterioration or failure.[1.1] A recent study[1.2] has suggested that $84 million could be saved annually by on-board surveillance of those components for which immediate identification of a failure would permit remedial action before an accident occurred. Electrical control of the pneumatic brakes would contribute to the more effective use of rolling stock by allowing the formation of longer trains, especially in winter, and their movement at higher speeds than is currently possible.[1.3,1.4,1.5] Furthermore, the wear and tear on the coupler components would be reduced with a consequent reduction in maintenance costs.

The nature and extent of communications systems on freight trains, except for two-way voice radio links, is indicated by the following examples:

( i) A remote control system, tradename LOCOTROL, has been used for a number of years to link a "master" locomotive to one or more "slave" units located at different points along the train. By means of two-way radio, brake, throttle, and other control settings are transmitted to the slave in a digital format and confirmed by "hand-shake" replies. LOCOTROL requires a source of power and must employ a sophisticated coding scheme to avoid interference from the wayside and from other trains using the same system.

( ii) Two substitutes for cabooses, called End-of-Train Units (ETU), have been developed recently, one by Union Switch called TRAILGUARD, the other by Glenayre called DIGITAIR. In both cases, the battery-operated device is attached to the knuckle coupler and connected to the air hose. Digitized tail-end air pressure is transmitted to the cab by radio at regular intervals. Neither of these caboose substitutes is in general use yet.

(iii) The oldest on-board communications link, other than the brake air hose itself, must be the electric transmission lines which control electro-pneumatic (EP) brakes. Although EP brakes were tried on freight trains in the 1880's, they were soon abandoned in favour of the new Westinghouse system in the 1890's. Later, about 1930, a few freight trains were equipped with EP brakes on a trial basis, but the results were not considered promising. A major problem in the early attempts to introduce EP braking on freight cars was the maintenance of transmission-line continuity through the large number, often a hundred or more, cars. The principal source of trouble has always been the inability of inter-car connectors to perform reliably in the freight railway environment.

The many hazard warning schemes which have been proposed, and in some cases demonstrated, which provide a signal only when the hazardous condition occurs, are not considered to use communications links in the context of this study.[1.6-1.9] Such one-shot devices are not likely to receive wide acceptance because they have the serious disadvantage that it is not possible to easily determine whether they are functioning properly. In comparison, systems based on the continuous, or periodic, measurement of a parameter such as temperature also automatically provide an indication that the measuring system is working.

Despite the problem of maintaining continuity, the train transmission line, or trainline, continues to be an attractive communications medium because of its simplicity, the relative simplicity of associated receiving and transmitting equipment, and its inherent ability to transmit power as well as signals. With these beneficial features in mind, Canadian National, Canadian Pacific and Transportation Development Centre sponsored, through CIGGT, a study and evaluation of a

number of techniques for coupling electrical signals between cars without the use of metal-to-metal contacts.[1.10] This work, carried out by this author from 1971 to 1973, revealed that inductive coupling was the only technique showing promise, and produced an experimental inductively-coupled connector mounted in a "glad-hand" air hose connector. Subsequent projects[1.11,1.12] under the same sponsorship refined the design and then had Brospec make a small production run of 120 units which were tested in a wide range of electrical and simulated environmental conditions. In May 1981, seventy of the inductive connectors were installed on thirty-five cars of a Dominion Atlantic Railway (DAR) captive fleet at Windsor, Nova Scotia.[1.13] At the time of writing, the connectors on the DAR train have operated without failure or damage for three years.

Each inductive connector is completely enclosed in a rubber capsule which is held in a protective housing mechanically similar to a conventional air hose connector. Electrical coupling is achieved through the magnetic fields of the transformer created by connecting two units together. The present units have a transmission efficiency of 92 per cent, a bandwidth of 16 kHz centred at 28 kHz, operate over a temperature range of -70° to +100°C and can pass 100 watts. With non-metallic housings, the connectors have an efficiency of 98 per cent, which represents the potential performance of the device. They appear to have the ruggedness and reliability needed of an inter-car connector and, because no metal-to-metal contacts are involved, are impervious to corrosion and dirt.

However, inductive connectors are considered by the railways to have two serious limitations:

( i) The devices have an internal loss of 0.36 dB, corresponding to an efficiency of 92 per cent, which for a single coupling is not significant, but for 100 cars would be prohibitive to power transmission. This attenuation is not an impediment to signalling if on-board power is available.

(ii) To achieve high efficiency, the connectors must be operated as a tuned transformer. Consequently, the usable passband is much narrower than that of a conventional connector.

The limitations of the tuned inductive connector, and the idea that technological advances in the decade since the previous study of coupling techniques may offer new solutions, led to the initiation of the present study.

## 2. OBJECTIVE

The objective of this study is to identify and evaluate new technology which might be applicable to the transmission of signals and power along freight trains, without the limitations imposed by the tuned inductive connector.

In the study conducted a decade ago, the focus was on techniques for transmitting signals between cars without using metal-to-metal contacts. The present study is much broader in scope in that, on the one hand, it is not restricted to conventional transmission lines while, on the other hand, it examines the current state of metallic-contact connector technology. Systems based on inductive coupling, other than the tuned inductive connector, are not excluded.

With regard to power transmission, only techniques for the transfer of electrical power from the locomotive to the cars were to be considered. Independent, on-board sources were not part of this study.

## 3. STATUS

All phases of the project have now been completed. Conclusions and recommendations arising from this study are included in this report.

## 4. INVESTIGATIVE PROCEDURE

Information gathering employed broad literature searches, consultations with connector manufacturers and users in the rail transport industry, and site visits. The literature searches used the data bases of INSPEC, TRIS and NTIS, plus manual searches of journals likely to have relevant articles. Very recent European and North American abstract indices whose contents had not yet been included in the data bases were also examined manually.

In all, well over one thousand abstracts from 1970 to the present were examined. There were two different approaches to the search in that connector technology was quite specific and well-defined, while the task of identifying new, relevant technology was broad and much less precisely defined. With regard to the latter, journal articles and special issues devoted to reviews and surveys of the state of electrical and electronic technology were sought for the period 1977 to the present. A patent search was carried out on connector technology appropriate to the railway application. No patent search for new technology in general was carried out, since the subject area was too imprecisely defined for this to be practical.

Product literature was obtained from manufacturers who were also consulted regarding the applicability of their products and techniques. Major manufacturers making connectors for use in the transportation industries are AMP, Amphenol-Tuckle, Cannon, Pyle-National, and VEAM (Litton). AMP, Cannon and Pyle were particularly interested in the possibilities of a new product line. During the early part of the project, a set of specifications for the ideal inter-car connector was developed to focus discussions with the manufacturers. These specifications are presented in Section 7.1.2. This direct approach to the connector industry was very fruitful.

Although passenger trains and rapid-transit systems operate in a much gentler environment than freight trains, and are subject to a much higher level of maintenance, it was felt that much could be learned about the reliability and problems of connectors in the rail environment from passenger and transit experience. Manufacturers of both passenger equipment and operating systems, as well as users, were consulted. These organizations included Bombardier, Glenayre, Hawker-Siddeley, Ohio Brass, WABCO, UTDC, VIA and the Toronto Transit Commission (TTC).

In addition to the above, a number of very useful interviews were held with people in the (U.S.) Federal Railroad Administration (FRA), the Transportation Systems Centre, the Association of American Railroads (AAR), Canadian National, Canadian Pacific and Minn-Tac Mines.

## 5. NEW TECHNOLOGY

For the purpose of this study, the term new technology includes:

(i) new developments in established and obviously relevant fields

(ii) truly new fields which have come to the fore during the past decade

(iii) technology that has existed for some time, but whose application to freight-train communication may be new.

Areas considered in the course of this study and falling in (i) above were connectors and contact technology, and VHF radio; in (ii) were optical fibres and electro-optics, microelectronics (integrated circuity, microprocessors), digital communications, and data encoding; and in (iii) were waveguides, inductive-loop communications and leaky transmission lines.

Microelectronics, digital communications and data encoding do not offer new concepts bearing directly on the transmission mechanism of a communications link. However, they have an indirect impact in that modern microelectronics permit low power requirements for quite sophisticated electronic systems, while data encoding can affect the channel capacity, error rate and reliability of a communications system. Furthermore, microprocessors can provide local intelligence which reduces the quantity of data that must be transmitted in sensory and control systems.

Recent development in satellite communications, large computers and robotics were not seen to have direct relevance to on-board freight-train communications.

## 6. GENERAL REQUIREMENTS

### 6.1 Communications Mode

To execute surveillance, hazard-warning and brake-control functions, a communications link must provide continuous two-way communications between cab and cars. The term "continuous" in this context includes

regular transmission of a quantity at intervals short enough that the quantity has not changed by a significant amount during the interval. Many of the hazard-warning schemes that have been proposed or demonstrated are based on signalling the hazardous condition when it occurs. The problem with such systems is that there is no simple way to regularly check whether they are in a state of readiness and will function when called upon to do so. In contrast, a system that continuously monitors a parameter is seen to be functioning as it supplies the observational data. Simple, one-shot hazard-warning systems give the alert only when a preset threshold is passed. Continous monitoring not only permits detection of threshold crossings, it allows the cab computer to recognize the onset of potential hazards by noting quantities which are starting to change abnormally. In other words, it can provide early warning of potentially dangerous situations.

It is assumed in this study that data will be transmitted and processed in a digital form. The reasons for choosing digital techniques over analogue are:

( i) Digital processing is not sensitive to attenuation in the medium or gain fluctuations in the on-board circuits, provided an adequate signal-to-noise ratio is maintained, and does not need amplitude calibration.

( ii) Microelectronic digital hardware can be fabricated in densely-packed chips which provide ruggedness and low power consumption.

(iii) The head-end (cab) logging and decision-making hardware will be some form of digital computer.

( iv) Digital data transmission lends itself to encoding against interference and errors.

( v) Digital modulation of a carrier frequency is relatively easy to implement.

( vi) Self-checking of the system's response to instructions and the self-diagnosis of faults are functions that can be readily included in the structure of a digital system.

(vii) By means of addresses and a specific data format, a digital system can communicate with different devices by means of a single transmission

channel. This technique of multiplexing instructions and responses on a single "bus" can realize considerable savings in transmission hardware.

References relevant to data transmission are 6.1 to 6.8.

## 6.2 Data Specifications

One piece of information that must be known before communications links can be assessed and compared is the source data rate, that is the rate at which data must be transmitted between car and cab. The data rate will depend on the quantity of information to be transmitted and how often it must be updated. For information transmitted in analog form, the corresponding quantity would be the information bandwidth. Since no firm data defining the on-board communications needs of freight service were found, the following model was adopted for this study. It must be borne in mind that this model is not a system design, but simply the means to establish an initial estimate of the quantity of data that must be handled using conventional data coding practice.

The sensory and monitoring system described below is more elaborate than would be required for immediate railway needs. For example, brake control was included, even though EP-brake strategies and hardware requirements have not been defined. The guiding philosophy behind this approach is that any communications link installed on trains for even modest initial applications must be capable of accommodating additional functions without expensive retrofitting and/or modification.

### 6.2.1 Car-to-Cab Communications

Sensory systems for hazard-warning and monitoring are as follows:

(a) Bearing temperature measured to four-bit accuracy, that is the temperature range of interest is covered by 16 intervals. The data generated by eight bearings are 32 bits.

(b) Up to four systems for monitoring car dynamics. These could include strain gauges for drawbar forces, and accelerometers to sense loose wheels, derailment, etc. Eight-bit data from each would give resolutions of one part in 256, or 0.4 per

cent on the measured quantities. Thus, the data generated could be as high as 32 bits.

(c) Systems for monitoring critical-component conditions, including the electronic hardware on board. Sixteen bits should be allowed for this function.

(d) Spare capacity of 16 bits to accommodate the additional requirements of special-purpose cars such as refrigerator or hazardous-commodity cars.

(e) A brake-state monitor to observe key brake system parameters to ensure that the brakes are functioning properly. Among these parameters could be air pressure, brake piston travel, brake lock status, and angle cock position. For this study, 16 bits have been allocated to brake-system monitoring.

The imaginary sensor system described above would generate a total of 112 data bits. However, encoding by an on-board microprocessor chip could, in principle, reduce the total number of bits. For example, smaller quantities, such as the differences or changes in parameter values between measurements could be transmitted. Also, the values of some parameters would not have to be updated as frequently as others. In other words, increased local intelligence on the car could reduce the amount of data that must be transmitted to the cab. However, for the present study, no special data compression coding is presumed.

All monitored data must be identified with the car from which it originated. Car identification codes based on serial numbers would require 50 to 60 bits to include all possible letter/number combinations. While such information could be stored in the permanent, on-board, electronic memory, an initializing scheme is envisaged in which the cars would be assigned numbers according to their positions in the train. An eight-bit word would thus accommodate 256-car trains. However, if there is a possibility of interference with other trains or services, a data block would be necessary to identify the train as well. The basic eight-bit identification code was used in this analysis.

Data from each car would be communicated to the cab every ten seconds. To maintain synchronization, this would be done in response to an interrogation command from the cab.

### 6.2.2 Cab-to-Car Communications

There is a variety of actual and proposed strategies and system configurations for controlling electropneumatic brakes. Some are described in references 1.3, 1.4, 6.9 and 6.10. Since the objective here is to simply establish a reasonable data requirement, the model will use digital control with the functions normal application, emergency application and release. Normal application would give eight levels of brake pressure and require three bits. Emergency and release need only one bit, but will be assigned two for additional security. An "off" or "other status" bit, which could be useful, makes up the total eight bits. An alternate brake scheme would make the brake pressure proportional to the time interval between a start code and a stop code. In either case, the digital command would have to be translated by on-board equipment at each car into the appropriate electromechanical valve action.

Brake command must be highly reliable and constructed so as to eliminate undesirable occurrences such as unintentional emergency brake application or false brake release. Consequently, inclusion of a higher degree of redundancy in the command, in addition to the coding described below, is reasonable. In common-mode braking, in which the same command is delivered to all cars, an address would not be needed. An identification block to announce the data stream as a brake command would be necessary in a free-running system.

Selective braking, where different brake commands could be directed to each car, or group-selective braking where different commands would be directed to different blocks of cars, offer opportunities to reduce brake shoe and wheel wear, and to control in-train forces. If selective brake application is desired, a car address and either parallel transmission to all cars or sequential transmission at a much higher rate, would be required. Also, if there is a possibility that the signals could interfere with those of other trains, the brake commands would have to carry train identification codes. Both common mode and selective braking will be considered, with an instruction consisting of an eight-bit brake command plus 16 bits of identification and error-correcting code, giving a total of 24 bits.

Because the amount of data to be supplied by the cars is quite small, it seems reasonable to use a common channel to all cars and to poll each car in sequence for the sensor data. This will require an interrogation command containing a command identification code, the address of the car being polled and a train identification code if needed. Only the address code of eight bits and an eight-bit command identification code has been used in the current model.

Other functions for which in-cab control would be beneficial to train operation are the opening and closing of angle cocks, the unlocking and opening of couplers, and the application and release of brake locks.[1.4] Because these are on/off operations which are executed infrequently compared to monitoring and brake control, they will need only a small number of bits. Their occasional issuance means that in practice they will have little impact on data rates.

### 6.2.3 Cab-to-Cab, Cab-to-Caboose Communications

A minimum of two two-way channels must be provided, one with a bandwidth of 2,000 Hz for LOCOTROL signals and one with 4,000 Hz for voice communications. End-of-train air pressure monitoring could be included in the general data format as a special-car requirement. Since the head end will know when it is interrogating the caboose, the head-end computer can be programmed to treat the response differently from regular data.

### 6.2.4 Link Length

A train length of 200 cars has been assumed in this model. However, an acceptable communications system will have to operate satisfactorily on trains of any length up to the system's limit. Although the figure of 200 is larger than current practice, it is reasonable to expect longer trains to be possible with on-board communications and, in fact, longer trains would more fully exploit the operating cost reduction potential of this innovation. With 15 m long cars, the link length would be 3 km.

### 6.2.5 Data Rates and Bandwidths

The monitoring data and identification code for one car total 120 bits. If the system is to accommodate up to 200 cars, the possible data rate is 24,000 bits every ten seconds. The basic interrogation command contains 16 bits and must be transmitted 200 times in ten seconds. The common-mode brake command of 24 bits would be transmitted ten times per second. If it is assumed that only one source would be transmitting at any given time, the total amount of data that must flow through the link in one second, regardless of direction of travel, is (2,400 + 320 + 240) = 2,960 bits.

The data rates and bandwidths required by this model are quite modest compared to the capabilities of most communications media. For example, the data sets and modems used to link terminals to computers operate in the 2,400 to 9,600 bps range. For selective braking, the brake command defined earlier, plus a car identification code, would require 32 bits which would have to be transmitted to 200 cars in 0.1 seconds. This would required 92,000 bps. The requirement that brake data be transmitted every 0.1 seconds is arbitrary. Frequent transmission is a means of creating redundancy, and hence reliability, and of assuring that the system is functioning. If one second can be taken to assign the brake instructions to 200 cars, which is more than an order of magnitude faster than the response time of the current common-mode air system, then the required bit rate would be only 6,400 bps. Group-selective braking would require a bit rate intermediate between common-mode and fully selective braking; the actual rate would be proportional to the number of groups into which the consist is divided. Updating the common-mode braking data every second instead of ten times per second would have little effect on the total data rate.

In practice, digital transmissions usually require introductory codes for identification, bit and word synchronization codes, codes indicating the status of the link functions, and error-control codes. These details cannot be addressed until a data format and coding algorithm are chosen. These requirements could double the number of data bits in the final data stream. Thus, the final estimated data rate in the proposed common-mode model would be about 6,000 bits per second (bps), and could be as much as 134,000 bps in the fully

selective system. However, a system updating commands every second would need only 18,800 bps for selective braking.

The minimum bandwidth requirement for data transmission plus a 4 kHz voice channel, a 2 kHz LOCOTROL channel, and 2 kHz guard bands between each of these active bands would be between 20 and 150 kHz, depending on the brake-command system. The required data bandwidth is based on an assumption of one Hertz per data bit. This is greater than necessary, since modern modems (modulation-demodulation interfaces) can employ data compression in which data rates two to four times the bandwidth are transmitted by multi-level bit coding, phase modulation or quadrature-amplitude modulation. In a specific system, the modulation technique and the physical nature of the link may increase the required bandwidth. For example, if two-way communication requires different channels for transmission in each direction, the spectrum space required will be doubled. As a general rule, the greater the modulation system's resistance to intereference, the greater will be the bandwidth it requires.

If the model assumptions with respect to either the data content or the time allowed between updating prove to be understated, the basic requirements could increase dramatically. As it stands, the model probably overstates rather than understates the final data rates. There is little further that can be done without a firmer definition of railway requirements.

## 6.3 Noise and Error Rates

Noise and interfering signals will cause errors in the data stream. Sources of noise include the EM radiation created in the switching of heavy currents as occurs in the locomotive, EM fields from adjacent power lines, radio transmissions external to the data link, etc. Since some noise is inevitable in any system the critical factor is the signal-to-noise power ratio (SNR). The minimum SNR acceptable can only be established when the coding system and acceptable error rate have been determined. For the model introduced above, one error in data every 1,000 hours of operation would give a bit error rate of $10^{-10}$. This is a very high degree of reliability, and may be an excessive demand on the system. On the other hand, this bit error rate does not represent the failure rate of the system, because error detecting and

correcting codes can introduce many orders of magnitude of improvement into the message reliability. The error rate for monitoring need not be as high because the consequences of very occasional bit errors would not be great. In contrast, the brake control data should be highly redundant and coded to withstand interference. At this moment, not enough is known of railway operating requirements with regard to false alarms, and the nature of interference and noise expected, to permit further analysis.

## 6.4 Power Requirements

Modern integrated-circuit technology, especially CMOS technology, has made possible the fabrication of quite complex digital hardware containing the equivalent of tens of thousands of transistors, yet consuming only a small fraction of a watt of power. Most sensory devices require very little power and some even extract their power from the source being measured as, for example, in the case of thermocouples. If the most modern microelectronics techniques were used to put the complete on-board system on one or a small number of "chips," the total power required for data processing and encoding activities could be less than one watt.

In addition to this data processing requirement, power will be needed for the transmission of the data stream. The actual power required will depend very much on the communications medium selected and on the interference to which it is susceptible. For data communications, the power required on the individual cars has been taken as one watt plus the power required to operate the link.

One type of electromechanical valve used for controlling air brakes requires 72 V and 0.25 A, or 18 watts. Reference 1.4 describes a valve operated by a latching solenoid which requires a 1 A surge for 10 msecs at 12 V to execute an open or a close function. This corresponds to 0.12 Joules per operation, and a peak demand during execution of 12 watts. Lower peak demand could be achieved by providing local energy storage to accommodate the surges. If power could be delivered for ten times the demand interval, the peak power would be reduced by a factor of ten, but so would the reaction time of the control element. In the example above, where the solenoid operated for 10 msec, the repetition rate would be ten times per second instead of 100. Local storage

elements could be batteries, capacitors or mechanical devices such as compressed springs. It is conceivable that devices with lower power requirements could be developed. However, it is important that the electromechanical system be sufficiently robust that vibration and jolting of the car could not cause accidental tripping of the brake system. To achieve this robustness, the minimum brake system requirement has been set at 10 watts minimum and 20 watts maximum per car. Brake control on a 200 car train would thus require between two and four kilowatts.

## 6.5 Safety and Fail-Safe Operation

For the safety of personnel, voltages in any of the on-board equipment should not exceed 150 volts. Microelectronic equipment, which normally operates with voltages of ten or lower, would pose no safety problems. However, the specific case of transmission lines on cars warrants special attention. If railway personnel have to handle connectors in all weather conditions, it would be essential that a system of interlocking breakers be implemented, either locally on the cars or at the cab, to ensure that the line is not alive when handled.

It is also important that personnel not be exposed to unsafe levels of electromagnetic (radio, microwave), optical or other radiation. A safe level for electromagnetic radiation in the VHF and microwve range is about 1 $mW/cm^2$ total body exposure. Exposure to high intensities of microwave radiation or laser light can cause burns and blindness.

Any electrical or mechanical system will eventually fail. The objective in designing highly reliable systems is to make the time between failures as long as possible, to ensure that the cause of failure, when it occurs, can be easily and quickly diagnosed, especially in complex systems, and to keep repair time as short as possible. One of the advantages of digital control is that the microprocessors in the system can be programmed to put the system into a safe mode of operation if the commands become unintelligible either through failure of the link or failure in the on-board equipment. The microprocessors can also be programmed to conduct diagnostic checks on the system and themselves.

It is essential that provision be made for continuous monitoring of link integrity. This is of paramount importance in links carrying

brake commands. Acceptable communications-link techniques must be able to accommodate configurations which permit continuous self-checking. Loop arrangements which send data and commands around a loop in opposite directions offer some advantages in reliability and fault diagnosis. If possible, failure of on-board equipment at one point in the train should not render the whole communications system inoperative. Parallel redundancy can be very effective in improving system reliability. Suppose, for example, that the probability that the system would be operational for a given length of time is 0.999. Then the reliability of two such systems operating in parallel would be $1 - (1-0.999)^2 = 0.999999$.

It is also essential that the overall communications, monitoring and control system be capable of identifying and reacting to an accidental separation of the train into two parts. Control of the lead portion must be maintained and the separated rear portion must automatically go into a safe braking routine. Also, if power is transmitted along the train, there will be a sudden loss of power in the rear section at the moment of separation.

## 6.6 Attenuation and Power Distribution

The importance of attenuation in transmission media can be quite different for power and signals: voice and data signals are often allowed to drop 30 dB (i.e. by a factor of 1,000) or more between amplifiers (repeaters) on telephone lines. A drop of only 1 dB in a power distribution network would represent a power loss of 20 per cent. Fortunately, power transmission can be accomplished at low frequencies, or zero frequency in the case of direct current, where the attenuation is least. In the railway situation, where an on-board transmission line requires an inter-car coupling device, the attenuation of the device must also be taken into account.

Transmission efficiency, R, is defined as the ratio of the power flowing out of a system or device to the power flowing into it. Loss or attenuation in decibels is:

$$L = -10 \log R \quad \text{(dB)}.$$

Subscripts 1, v and c will denote quantities associated with the line, the vehicle and the coupling device, respectively. Thus, for the transmission line on one car and a connector pair:

$$R_v = R_l \, R_c$$

and for N cars,

$$R = R_v^N$$

The attenuation for one vehicle is:

$$L_v = L_l + L_c \qquad \text{(dB)},$$

and for N it is $NL_v$.

If the transmission line has a transmission efficiency of, say, $R_l$ = 0.99 and the coupling device has an efficiency of $R_c$ = 0.96, $R_v$ = 0.95. A train of 100 cars would have an overall transmission efficiency of $0.95^{100}$ = 0.006 or 0.6 per cent. The attenuation in this situation is 22.3 dB. While such a system would transmit signals well, it would be useless for delivering power.

It is interesting to compare the attenuation experienced by a signal transmitted by radio. Assuming the usual "whip" type antennas, a distance of 3 km and a frequency of 300 MHz, the ratio of the power at the terminals of the receiving antenna to the power delivered to the transmitting antenna is $2 \times 10^{-9}$. This corresponds to a loss of 87 dB. Actually, these ratios indicate the fraction of the transmitted power intercepted by the receiving antenna, the rest being radiated into the surrounding space.

It is important to remember that when electric power is available at the individual cars, regardless of how the power is provided, signal attenuation in the transmission system becomes a secondary consideration. Signals can be amplified at each car to compensate for the attenuation experienced in travelling from one car to another along the train, or from the cab directly to the car in systems employing a direct link.

Consider a general power delivery system in which the power is propagating as some form of travelling wave. The power taken by an individual car can be represented by a load extracting a constant fraction of the available power. This would be the situation if a simple resistive load were connected across a two-wire line, provided that the fraction of power absorbed were not large. If a given amount of power, $P_v$, is required at each car and the absorption fraction is p, then there must be $P_{aN} = P_v/p$ available at the last car. At the second from the last car there must be $P_{a(N-1)} = P_{aN}/(1-p)$, and at the $n^{th}$ car from the end, $P_{aN}/(1-p)^{n-1}$. Thus, the power input to the first car in an N-car string must be $P_{aN}/(1-p)^{N-1}$ or $P_v/P(1-p)^{N-1}$. The lowest possible input power for a given N and $P_v$ occurs when $p = 1/N$, and is:

$$P_{MIN} = (N/N-1)^{N(N-1)} P_v$$

which is very closely approximated by:

$$P_{MIN} = 2.7 \; N \; P_v$$

when N is greater than 10. As an example, consider delivering 10 watts to each of 100 cars. Choose a constant absorption fraction, a necessary condition if equipment on all vehicles is identical, of 0.01. Then, input power to the transmission system will have to be 2,700 watts instead of the 1000 watts actually needed. With 200 cars, the same system would need 7,400 watts at the input. Furthermore, the vehicles near the head of the trains would be extracting excessive amounts of power.

An exception to the general rule stated above for transmission of power at high frequencies is the situation where the loads are integral numbers of half-wavelengths apart along the transmission medium. The loads then appear to be connected in parallel at the source. The problem with a distribution system operating in this mode is that the length of transmission cable or waveguide, etc., on each car must be an integral number of wavelengths long, regardless of the length of the car. At short wavelengths, expansions and contractions with temperature changes will certainly change the electrical length of the line and disturb the loading condition.

The discussion above has not included attenuation in the medium, which would only compound the problem, since power must also be supplied to the lossy elements of the transmission system.

The conclusion to be drawn is that efficient power distribution will be achieved when propagation effects can be ignored between loads. That is, when the wavelength of the power-carrying waveform is greater than the length of the train. In that case, the loads appear to be connected in parallel across the source, and share the available power equally. Since power transmission should be done at low frequencies, the conventional two-conductor transmission line would seem to be the best choice.

## 6.7 Other Systems

It is interesting to compare the model presented here with other railway data transmission systems. The UIC proposed specifications[6.11] for the transmission of information through a train line call for the updating of monitor information every three seconds. The maximum train length considered is 80 cars. Only changes in data need to be transmitted. A safety-related message from an on-board monitor must identify the car. "Safety monitoring" includes monitoring of running gear when in motion, a check on continuity of the train, movement of load rear lamps status, and door status (open or closed) on passenger trains. Instructions, other than brake commands, are for heating and air-conditioning (on/off), lighting, closing and opening doors, loudspeaker system switching, controlling stop cocks individually, and the selective operation of the automatic coupler.

Voltages will be 240 V with currents of up to 20 A in four circuits for operating the electromechanical devices. The system must operate with only a transmission line on a car. That is, the transmission of information must not depend on active equipment on the individual cars.

A two-wire data line carrying multiplexed digital data is assumed. The data channel is expected to be located below 150 kHZ. The instruction set and monitoring requirements would suggest quite modest bit rates. There will also be a carrier-frequency telephone. The bit-error probability on safety information should not exceed $10^{-10}$. Less critical information can have bit-errors of $10^{-7}$. Equipment must have

a reliability corresponding to a Mean Time Before Failure (MTBF) of 20,000 hours.

The End of Train Units (ETU) use radio communications and transmit the air pressure data at 1,200 bps. Pressure measurements are made every second to an accuracy of ±1 PSIG in the range 0 to 125 PSIG. In addition, the ETU has provision for five status monitors, that is "on/off" conditions. The maximum delay in signalling a status change is 5 seconds. Transmissions contain, in addition to air pressure and status information, identification of the unit, a synchronization code, 18 bits of BCH error detection code with one bit or two adjacent bits of error correction. (BCH is a cyclic error check code which provides a high degree of security against unrecognized errors.) Transmission takes 260 msec. The bit error rate at 0 dB signal to noise ratio is $10^{-4}$ on actual transmitted sequences. Power required by the monitor unit is a 12 V, 4 A Nicad rechargeable battery which gives 500 hours operation between charges (information from reference 8.3).

The original LOCOTROL system for controlling remote locomotives by radio signals from a master locomotive is another example of in-train digital communications.[8.1] All data are transmitted as a frequency-shift-keyed (FSK) signal. The two sub-carriers used for the FSK are 1,500 Hz and 2,500 Hz. Each information transmission is preceded by a 30 msec "mark" tone which distinguishes a message from noise. The logic system accepts a mark tone longer than 20 msec while rejecting as signals any tones shorter than 20 msec. A message consists of 50 bits and lasts 220 msec. Eleven bits are the address code identifying the originating point (master locomotive) to prevent transfer of information between locomotives of different trains on the same VHF frequency. Thirty-two bits of control information are transmitted, plus a six-bit Bose-Chandhuri (BC) code for error checking. An additional bit identifies whether the transmission is from a master or a remote locomotive. Masters accept only from remotes, and vice versa.

Command functions are transmitted whenever there is a change of any control function or, if no changes have occurred, every 21 seconds. The receiving locomotive reports back within 100 msec to give confirmation that the correct message has been received. If the remote fails to receive a transmission from the master or vice versa within 45 seconds, a no-continuity condition is indicated on the cab display. Emergency

procedures are built into the system in case of loss of continuity or the train breaking in two.

## 6.8 Subdivision of Systems

Potential on-board communications techniques can be divided into two categories:

( i) those that could, in principle, carry both the power to operate on-board equipment and the data signals

(ii) those that can carry only the signals.

Techniques in the latter category require another means of providing on-board power. Systems that could in principle carry power and signals are conventional copper-wire transmission lines and microwave waveguides. Examples of systems limited to signals only are VHF radio, optical fibre lines, and inductive coupling either from car to car or through a wayside medium. Note that the tuned, inductively-coupled link falls between the categories in that it carried signals well, but can deliver only small amounts of power, less than the power needed to operate EP brakes on long trains.

A wide variety of schemes have been suggested for providing power at the cars. These include conventional generators operating off the axles or driven by the air supply, piezoelectric and electrodynamic accelerators responding to vibration, solar cells, batteries, thermal energy from bearings, etc. Unless an on-board power source is found whose ruggedness, lifetime and level of maintenance are acceptable to the railways, none of the second category of communications links will be viable.

In the sections which follow, the transmission systems are classified according to their transmission concepts as follows:

( i) on-board transmission media: those systems which require all cars in the train to be equippped in order to provide a cab-to-car link, and

(ii) external transmission media: those systems which can communicate between cab and individual cars without requiring all cars to be equipped.

Section 7 deals with on-board media: transmission lines, optical fibres and waveguides. Within the sub-section on transmission lines, the problems of electrical connectors for freight-train applications are dealt with in some detail. Section 8 discusses systems employing external media: radio, inductive coupling to transmission lines, leaky coaxial cable and a transponder link. Section 9 gives an overall assessment of the technologies described and Section 10 presents the recommendations arising out of this study.

# 7. ON-BOARD TRANSMISSION MEDIA

## 7.1 Transmission Lines

### 7.1.1 Advantages and Disadvantages

The term "transmission line" in the context of this work refers to any system of two or more insulated conductors running continuously from one end of the train to the other. A true transmission line has a constant cross-section and propagation characteristics which are constant throughout the line. There are a variety of physical configurations, each with its special properties.

A twisted-pair telephone line consisting of 22 gauge wire has a typical attenuation of 5 dB/km at 50 kHz. In this type of cable, attenuation increases with frequency as $f^{\frac{1}{2}}$ but crosstalk toward the far end of the line increases as $f^2$. Twisted pair is limited to less than 1 Mpbs for a 1 km length. Several twisted pairs can be carried in a common jacket to provide several parallel channels. This can partially offset the limited capacity of a single pair. Coaxial cable consisting of an inner and an outer concentric conductor offers several conveniences. The fields are confined to the space between conductors; therefore, the outer conductor is also the shield. Braided outer conductors are often used for flexibility, but braid is an incomplete shield. Complete shielding requires a solid outer conductor. Attenuation in 12.5 mm ($\frac{1}{2}$ inch) diameter coaxial line with solid outer conductor is from 1 to 3 dB/km at 1 MHz, and 7 to 9 dB/km at 10 MHz. Attenuation of coaxial lines of the same characteristic impedance and employing the same dielectric material is inversely proportional to cable diameter. Data transfer rates are proportional to $(a/L)^2$, where a is the cable diameter and L is the length of the line. If the length-bit-rate

product were about 20 Mbps-km, the rate would be 5 Mbps for a 2 km length train, because of the $L^2$ dependence. In the freight train application, either the twisted-pair type or the coaxial cable would be appropriate and adequate. (Note that single-conductor transmission lines, that is waveguides, are not included in this definition and are dealt with in Section 7.3.)

Transmission lines offer the following advantages in the freight train application:

(1) They are capable, in principle, of distributing the 2 to 4 kW of power required by an EP brake system on trains of up to 200 cars.

(2) They can provide a communications channel for digital data and/or analog signals. Properly designed twisted-pair lines could transmit up to several hundred kbps, while coaxial cable could handle 1 to 10 Mbps, without repeater amplifiers in the length of a 200-car train.

(3) By means of a set of carrier frequencies or the inclusion of several conductors in a common structure, transmission lines can carry power and a number of signal channels simultaneously.

(4) The conductors can be enclosed in a shield to provide a high degree of immunity from external electromagnetic interference, and to ensure that the on-board system does not interfere with other services. Shielding would require the conductors to be enclosed in a conduit, since braided shielding is imperfect. Studies carried out by the ORE have shown that the continuity of the shielding from car to car is very important.

(5) Communication by transmission lines is unaffected by tunnels, terrain, wayside equipment and other trains.

(6) Equipment to interface between the signal sources and the transmission medium is very simple compared to other media.

(7) The inherent technological simplicity of a transmission line means that maintenance and trouble-shooting would require neither high skill levels nor complex equipment.

(8) Simultaneous two-way communication within the same frequency band is possible on two conductors in the same way that voice communication takes place on telephones.

(9) The integrity of the train consist and the continuity of the link can be easily monitored by sending a continuous signal from the head-end to the tail-end and back.

(10) Communications systems employing transmission lines have system lifetimes of 20 to 40 years.

Despite the many advantages offered by transmission lines, there are some important disadvantages to their use on freight trains:

(1) Every car in the train consist must be equipped with a transmission line to provide continuity throughout the length of the train. This would introduce a serious inconvenience when assembling trains which include equipped and unequipped cars. While a small number of unequipped cars could be included by means of jumper cables, the benefits derived from monitoring and EP brakes would quickly diminish if the number of unequipped cars were large. In contrast to the general service application, transmission lines could be installed on all the cars of unit trains, captive fleets and special-purpose integral trains dedicated to the efficient movement of specific products.

(2) If added to the present coupling equipment of freight cars, the inter-connection of lines between cars would have to be done manually. This has important implications for coupling and uncoupling time and for the type of employee who will undertake the task. If and when an automatic coupler is introduced into the North American freight scene, the electric connections would most likely be an integral part of the coupler head, along with the air-pipe connection.

(3) Past experience indicates that inter-car connection techniques have not proved adequate for general service use in the freight environment. The maintenance of continuity through the inter-car connection has been an ever-present problem. Therefore, a viable transmission line will be

possible only if an adequate inter-car connector can be developed.

Automatic coupling of freight cars was studied in Europe and North America in the 1960's and early 1970's. However, the subject seems to have been abandoned by the mid-1970's in North America, and it is not clear at present whether further work toward automatic coupling can be expected in the future. Therefore, for this study it has been assumed that the inter-car connection scheme will be either manual or an automatic system independent of, and not interfering with, the regular coupling-up gear.

The concept of on-board transmission lines is clearly not new. The physical and electrical characteristics of lines are well known and could adequately meet the requirements of the on-board communications link. The key area to which new concepts and new technology need to be applied is the inter-car connector.

It is of interest to note that the transmission lines recommended by the UIC for communications on European trains are the loudspeaker cable and the automatic coupler cable. The loudspeaker cable has 12 conductors with a common sheathing. Connection between coaches is effected by manually joining flexible cables. Line attenuation is 3.2 dB/km at 16 kHz, 6.0 dB/km at 50 kHz, and 8.1 dB/km at 100 kHz. Characteristic impedance is approximately 200 ohms. The automatic coupler line has four wires for controlling electropneumatic brakes, two wires for the supply of current to the equipment of the vehicles, and a pair of shielded wires for transmission of information. The resistance of the brake control and power lines are 3.4 ohms/km and 1.24 ohms/km, respectively (6 $mm^2$ and 16 $mm^2$ cross-section areas). The shielded information line has a resistance of 13 3 ohms/km and a characteristic impedance of 75 ohms. Line attenuation is 1.7 dB/km at 20 kHz, 3.5 dB/km at 50 kHz, and 5.2 dB/km at 100 kHz. The shielding of the loudspeaker cable is continuous and not grounded to the car structure, while the shielding of the automatic-coupler line is terminated at each end of the car and is not continuous through the coupler.

References relevant to the discussions above are 1.2, 1.3, 6.2, 6.11, and 7.1 to 7.4.

### 7.1.2 Connector Requirements

To assess the potential of existing connector technology to solve the inter-car connector problem, it is first necessary to establish what characteristics the ideal connector would have. The specifications outlined below are an attempt to do this. Such specifications are also an aid to identifying connector configurations which can be readily eliminated from further consideration. The ideal inter-car connector will have the following characteristics:

(1) A quick connect/disconnect coupling mechanism which pulls apart at a specific pulling force. The coupling mechanism must not be susceptible to jamming or other malfunction due to particulate matter or freezing moisture.

(2) An interconnection system which will permit mating regardless of the way the cars are oriented in the train consist.

(3) A good environmental seal against moisture when connected.

(4) The ability to be left unconnected and exposed to weather for weeks at a time, yet reliably make good contact when re-connected. Tentatively, the acceptable probability of a bad contact in reconnection has been set at less than $10^{-5}$. That is, there could be a bad connection requiring some form of remedial action once in every $10^5$ connections. Remedial action would be anything from cleaning contacts to replacing the connector. The figure of $10^5$ corresponds to assembling five hundred trains of two hundred cars each and finding that a repair had to be made on one car.

(5) The ability to be connected or disconnected by one man in 15 seconds or less. This corresponds to 25 minutes on a 100-car train, 50 minutes on a 200-car train.

(6) Voltage between conductors will be limited to 150 volts rms. The current-handling capacity to deliver adequate instantaneous power, as described in Section 6.4, to 150 cars would be 20 amps rms. A more sensitive electromechanical valve and/or local storage could conceivably reduce this requirement to less than 2 amps.

(7) The minimum number of contacts is two. This would provide one, two-conductor circuit on which power and signals would be multiplexed. A third contact to provide shielding continuity would be a wise precaution. It may be deemed desirable to have a larger number of circuits to provide redundancy and to separate power, signal and brake-control lines. In any event, the number of contacts needed would probably not exceed ten.

(8) Bandwidth capable of handling the data rates and, if desired, a voice channel. The exact value will depend on the quantity of data, brake strategy and coding scheme. However, from the data model it is clear that bandwidths of the order of 100 kHz would be adequate for power and multiplexed signals on a single pair of conductors. Multiple parallel circuits would reduce the bandwidth requirement.

(9) Adequate shielding against locally-generated electro-magnetic interference from the locomotive, power lines, and the signals in the wayside and passing trains. ORE studies of data transmission through the lines in automatic couplers and along the public address circuits indicated that the continuity of shielding through the intercar connection was extremely important in minimizing electrical interference.

(10) The ability to operate properly over the ambient temperature range of -50°C to +60°C.

(11) Ideally, have a lifetime of 20 years between changes. However, depending on the cost of the connector and the ease with which it can be changed a shorter lifetime could be tolerated. An eight-year lifetime would correspond to the expected life of rubber components such as the brake-line air hoses.

(12) Estimates of the number of connect/disconnect cycles to be expected in general service range from 3 to 25 times per month, according to the railroads. A value of 10 times per month is assumed as the typical lifetime average rate, which gives a total number of cycles of 960 in eight years, or 2,400 in 20 years.

### 7.1.3 Reliability, Failure Rates and Mean Time Between Failures (MTBF)

In addition to the likelihood of a failure due to deterioration of the engaged contacts while in service, the failure rate in the railway application must include the likelihood that when two members of a family of connectors are mated, a satisfactory circuit may not be completed. Thus, the failure rate must take into account the environment and usage at all times. Not only the obvious factors such as corrosion, vibration wear, and insulation breakdown, but also the likelihood of damage to the connector rendering it unserviceable must be included.

If the failure rate is F, then the reliability for a train of N cars, $R_N$, is:

$$R_N = \exp(-FN)$$

Since FN is expected to be a small number, the exponential can be approximated by the most significant terms of its series expansion so that:

$$R_N = 1 - FN$$

With the proposed values of $F = 10^{-5}$ and $N = 200$, $R_N$ is 0.998. In other words, two trains in one thousand would be expected to have bad contacts.

Attempts to obtain failure rate information on commercial connectors have not been successful. Test procedures used in evaluating connectors are not directed toward the conditions under which they will operate in the freight train application. Consequently, it is hard to make reliability estimates from the manufacturers' published data.

A mathematical model for estimating connector failure rates in military electronic systems is described in MIL-HDBK-217D (1982), "Reliability Prediction of Electonic Equipment."[7.5] The failure rate model for a mated pair of connectors is:

$$F_p = F_b \ (E \times P \times C) \text{ failures}/10^6 \text{ hours}$$

where: $F_b$ = a base failure rate dependent on the operating temperature and the type of insulating material employed

E = an environmental factor determined by the working environment and the nature of the usage

P = a factor determined by the number of active pins

C = a cycling factor depending on the average number of mating and unmating cycles per 1,000 hours.

Section 5.1.12.1 of MIL-HDBK-217D gives equations defining the coefficient in terms of the appropriate parameters. Tables of values are provided for convenience. The data apply to circular multi-pin, coaxial radio-frequency, and power connectors. Parameters to be specified are the type of insulating material, contact size and current carried. The lowest base failure rate ($F_b$) occurs with insulators of group B, examples of which are diallyl phthalate, melamine, fluoro silicone, silicone rubber, polysulfone and epoxy resin. Typical values of $F_b$ in failures per million hours are:

| °C | $F_b$ | °C | $F_b$ |
|---|---|---|---|
| 0 | 0.004 | 60 | 0.019 |
| 20 | 0.007 | 80 | 0.030 |
| 30 | 0.009 | 100 | 0.046 |
| 40 | 0.012 | 200 | 0.463 |

On the assumption that contacts will be sufficiently large that the temperature rise will not be great, it seems reasonable to adopt a value of 0.01 for $F_b$. The active "pin factor," P, is 1.55 for three contacts, 1.87 for five contacts, and 2.58 for ten contacts. For discussion, assume five pins with two for power, two for signal and one for shield continuity. The cycling factor is given in terms of mating and unmating frequency per 1,000 hours. Values of C are 2 for 0.5 to 5 cycles per 1,000 hours and 3 for 5 to 50 cycles per 1,000 hours. This factor depends on the nature of the freight service, but would fall within the 5 to 50 range; therefore, C = 3 in this calculation. The environmental factor, E, is established for each type of military application Some examples are:

| Environment | MIL-SPEC | Lower Quality |
|---|---|---|
| Benign ground installation | 1 | 1.5 |
| Space flight | 1 | 1.5 |
| Airborne | 5 | 1.5 |
| Naval, sheltered | 5.3 | 11 |
| Ground mobile | 8 | 25 |
| Airborne, fighter plane | 10 | 25 |
| Missiles | 8.5-12 | 17-24 |
| Naval, unsheltered | 13 | 27 |
| Undersea equipment (prolonged exposure to salt water) | 25 | 50 |
| Missile launcher | 29 | 58 |
| Cannon | 490 | 970 |

Unfortunately, none of these applications corresponds well with the environment and usage on freight trains. Quite arbitrarily, a figure of 30 will be used. This is representative of the harsher environments, but not the harshest. With the numbers chosen above, the failure rate for a connector pair is (0.01) x (30) x (1.87) x (3) x $10^{-6}$ = 1.68 x $10^{-6}$. The mean time between failures (MTBF), defined as 1/F, would be 69 years.[7.7]

The main difficulty with this calculation is that a reliable value of E is not known for the inter-car connector application. It was seen above that the value of E for military applications spans a range of more than two orders of magnitude. Some reliability figures obtained for connectors on rapid transit vehicles give a failure rate of 5 x $10^{-6}$ for large connectors, normally mated but exposed, 1 x $10^{-6}$ for small connectors, and 2 x $10^{-6}$ for the contacts in the automatic inter-car connector. These figures fall in the same range as the estimate above, which suggests that the harsher freight environment should be characterized by a higher value of E. The coefficients P and C are governed by quantities for which reasonably accurate estimates can be made. However, it is clear that more information must be obtained regarding the inter-car connector environment before reliability predictions can be made with confidence.

The other side of the reliability question is knowing what an acceptable MTBF would be. Consider the air-hose with glad-hand connector. It is the freight-car component which most resembles in usage and vulnerability to damage the electric cable and connector. Canadian

Pacific has provided information which indicates that while the expected life of the air hoses is eight years, they have to be changed on average every four to five years in some types of service.

Despite the uncertainties in the estimation of the MTBF, the fact that it is more than ten times longer than the change interval for the air hoses suggests that the traditional electrical, mechanical and chemical factors leading to the deterioration of connectors will not be the principal factors determining the failure rate in the railway application. Since it is unlikely that electric cables and connections would be more rugged or less vulnerable than the air hose and its connector, it seems reasonable to speculate that the primary causes of connector failure will be damage, inappropriate treatment, vandalism and the other "failure mechanisms" peculiar to the railway environment.[7.6,7.7,7.8]

### 7.1.4 Causes of Connector Failure

Common causes of connector failure identified with the railway environment are outlined below.

(1) Complete absence of a connector. A frequent occurrence on passenger trains equipped with electro-pneumatic brakes in the 1940's was the tearing off of connectors because the workmen forgot to disconnect them when uncoupling the cars. This is the reason for attaching considerable importance to the "pull-apart" requirement.

(2) Damaged contacts. Bent or misaligned pins will deform sockets such that they do not hold the pin securely. Subsequent vibration, or mating with a normal pin will result in an unreliable connection

(3) Damaged connectors. Either through vandalism or being struck accidently, a connector may have its coupling mechanism damaged, insulation cracked or shell damaged to the point that it is no longer moisture-proof.

(4) Negligent handling such as engaging connectors when they are wet or covered with snow.

(5) Mechanical malfunction. Coupling mechanisms, especially threaded types, may jam or seize-up as a result of moisture freezing, or particulate matter accumulating, in the mechanism.

(6) Accidental separation. It was observed that some push-in connectors held by the latching action of the receptacle lid were supported by security chains, and in some cases were held by wire because of the frequency of accidental partings.

(7) Cracking and deterioration of the insulator. Weathering, sunlight and temperature cycling can cause insulating materials to deteriorate. Moisture in small cracks in the insulator can result in partial shorting of the contacts. However, modern plastics technology has produced durable moisture-shedding dielectric materials.

(8) Detergent in the solutions used to wash cars has been found to leave a conducting film on connectors and caused partial shorting.

(9) Blocked sockets. Dust, dirt and moisture which subsequently freezes can block a socket and prevent the insertion of the plug.

(10) Corrosion. Poor contact, or even complete absence of continuity, can result from corrosion products forming on the contacts if the contact metal is not properly chosen.

(11) Wear. Wear mechanisms such as sliding, adhesive, abrasive and fretting wear eventually destroy the effectiveness of contacts in connectors that are subjected to frequent mating/unmating cycles. Fretting wear is the result of small amplitude oscillatory movement when mated contacts are subject to vibration or other cyclic stresses. Wear debris accumulates between the contacts and, if base metallic, oxidizes causing an increase in contact resistance. This is a significant failure mechanism with base metal contacts and with gold-plated contacts if the gold wears through to the underlying base metal.[7.9]

(12) Lack of maintenance.

### 7.1.5 Connector Coupling Mechanisms

Requirements 1 and 2 of Section 7.1.2 eliminate threaded coupling and conventional bayonet mechanisms from further consideration. Bayonet coupling would be of interest if the bayonets could be designed to disengage non-destructively.

Pyle-National and Amphenol-Tuckel offer several connector types in which a hinged receptacle cover serves as a latch to hold the connectors in the receptacle.[7.10,7.11,7.12] The cover has a lip, or in some versions a spring-loaded claw, which fits behind a ridge on the plug housing. The hinge of the lid is usually spring loaded to maintain the latching action, and to close the cover when the connector is removed. A well-known railway example is the receptacle and plug of the Pyle-National 27-pin WWPCJ connector on the jumper cables used for diesel locomotive control circuits. The plug section has a well-defined shoulder which the hook on the receptacle lid can grip firmly. The cover also protects the contacts against damage, dirt and weather when the connector is not in use. With proper choice of spring strength and appropriate shaping of the lip and ridge, it is possible to design a latch which gives way at a specified pulling force.

While the latching cover is not by any means a new concept, it is the technique chosen for such recent connector designs as the Trans-Power connector by Pyle-National and the C158/1 series by Amphenol-Tuckel (Figure 7.1). The Trans-Power is used in the LRC and some Amtrak vehicles. The series C158/1 connectors are designed to meet the International Railway Union (UIC) standards for control and audio signal transmission. It should be noted that the large retention forces on the contacts contribute substantially to holding the units together in these types of connectors.

A problem with the cover-latching technique is that the receptacle must be rigidly mounted so that the spring-loaded cover can be opened by one hand. This means that the system is appropriate for jumper cables where the receptacle can be mounted on the car, and not suitable when both connectors are attached to the ends of cables. (In this discussion the term jumper cable refers to a cable with connectors at both ends and not permanently attached to the vehicle.)

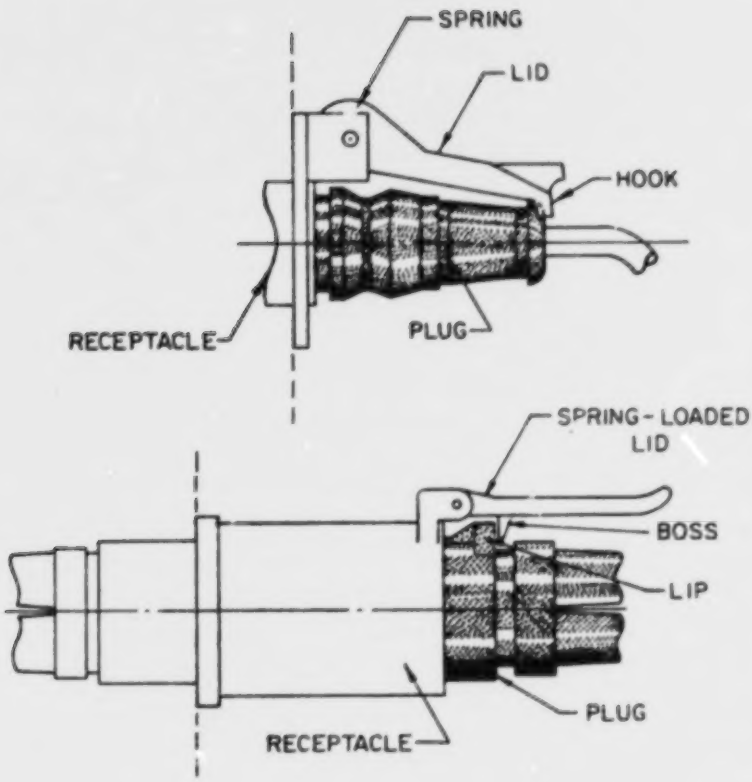



Figure 7.1 Two examples of latching lids. Upper drawing is in the style of the Amphenol-Tuckel connectors, the lower one illustrates the Pyle-National Transpower configuration.

The receptacle is sometimes angled downward at betwen 15° and 45° so that the cable can hang without a bend when it enters the connector housing. This also helps keep rain out of the receptacle. A problem that occurs is that as the connectors age, the latching mechanism deteriorates, either through wear of the lips and ridges, or weakening of the spring, or both, and allows the connectors to come apart. Horizontal alignment would seem to be preferable.

An interesting new latching arrangement has been identified in the Pyle-National C-line connector.[7.13] The C-line arrangement has two spring-loaded pawls, one on each side of the receptacle entrance, which are pushed aside as the connector is inserted. See Figure 7.2. When the connector is seated, the claw-like ends of the pawls close behind a ridge on the connector housing. As currently designed, the connector

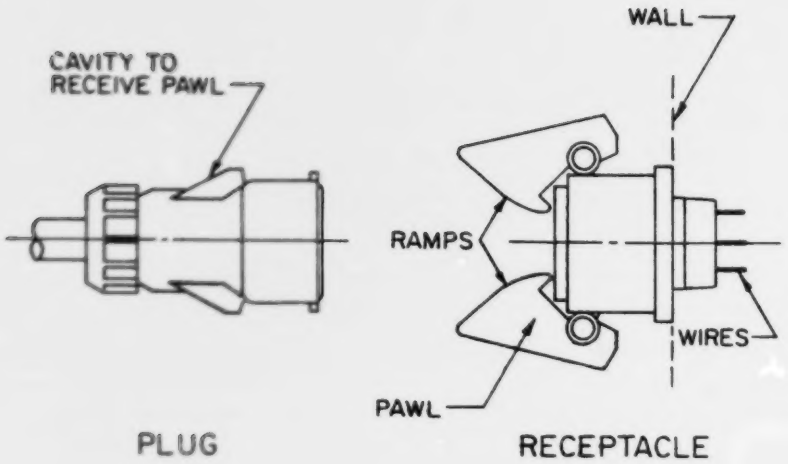



Figure 7.2 The Pyle-National C-Line connector for marine and harsh environments. As the plug pushes on the slightly concave ramp surfaces, the pawls move aside to let the plug enter, then close behind the cavity on the plug to hold it securely in place.

system is used to deliver power to refrigerated containers on board ships. In that application it is subjected to a harsh, damp, salt-water environment. The connector housing is made of DuPont Tefzel which is shatterproof down to -60°C, while the receptacle is made of molded fiberglass. One can readily visualize a hermaphroditic version of the connector with latching pawls that slide past each other on mating. This coupling concept meets the quick-connect requirement and could be designed to pull apart at a specified stress. (The present C-line latch is not intended to pull apart.) One aspect that is difficult to gauge is the effect of ice build-up around the latching components. This aspect is discussed further in Section 7.10.

Another housing which uses a pair of latching pawls is the type designed to hold the Anderson Powerpole contacts, described later in Section 7.1.6.[7.14] Nylon is used in the standard models offered, but harder materials, including metals, could be substituted for the nylon. The latches located on each side of the rectangular shell can be opened by grasping the connector between the fingers and thumb. The ends of the latches do not protrude beyond the contact structure and, therefore, are somewhat protected from damage. The latch and mating lip are not hermaphroditic; however, a pairing of the latches about a

line of symmetry on opposing faces could give hermaphroditic operation. A problem in winter conditions would be the build-up of ice under the latch handles, thus preventing the separation of the units. A flexible rubber jacket over the latch handles might be a solution.

The Ampower terminals,[7.15] designed by AMP as a quick disconnect for use on rapid transit motive units, are contacts which couple to each other by means of a mechanism resembling the glad-hand air-hose connector. These contacts are constructed of heavy-duty brass with silver plating. Sizes range from 95 mm long by 25 mm in diameter (3.75 in. by 1.0 in.) for 1/0 AWG (50 $mm^2$) wire, to 135 mm by 35 mm (5.31 in. by 1.375 in.) for 500 MCM (230 $mm^2$) wire. The coupling mechanism provides wiping action and develops high contact forces, the two basic requirements for reliable contact design. In its present form, considerable force is needed to make and break the connection. A modified version of this connector may be possible, or perhaps other variations on the "glad-hand" coupling principle. Two such connectors would have to be mounted in tandem to make a two-wire connection. This could prove to be quite awkward to connect because it would involve the alignment of two forked devices, a sideways motion and then rotation, in other words a three-dimensional alignment problem compared to the two-dimensional alignment normally encountered with connectors. The contact geometry could be difficult to house in a protective shell which would prevent accidental shock and provide a weatherproof seal. It could also be difficult to protect the contacts from environmental exposure when unconnected.

The ideas discussed above are taken from existing connectors. What follows is an idea which is, to the author's knowledge, as yet untried. A suggestion made on several occasions by people familiar with railway practice and connectors is to use the glad-hand air-hose connector as the housing, or shell, of an electrical connector. This concept differs from that of the Ampower terminals described above in that they have the coupling mechanism in the contact element itself, whereas what is suggested here is a glad-hand housing with contacts mounted in an insulator. Two possibilities arise immediately. First, the contacts could be mounted in a conventional glad-hand which would also carry air. Second, a completely separate connector could be installed which would have the contacts mounted in a hard rubber plug in place of the air hole. Both configurations meet all the mechanical

coupling requirements laid down for a connector in Section 7.1.2. However, the first would have the very attractive feature that electrical and air connections could be made simultaneously in one operation. Furthermore, it would appear possible, with perhaps only a slight increase in face area, to make an air-electric connector which would be compatible with an air-only connector. This would be useful during the period of transition to full implementation. From an electrical point of view, the basic requirements of wiping action and the application of contact pressure are inherent in the coupling principle. Figure 7.3 shows a possible contact configuration. The contacts could be different, for example a ball[7.16] or wiping edge bearing on a plate, but polarity is reversed through each connector. This characteristic would not be a problem if all power and signals were transmitted on ac carriers. If the contact elements were placed at the top and bottom (at "A" in the figure), the contacts would have to be identical, but

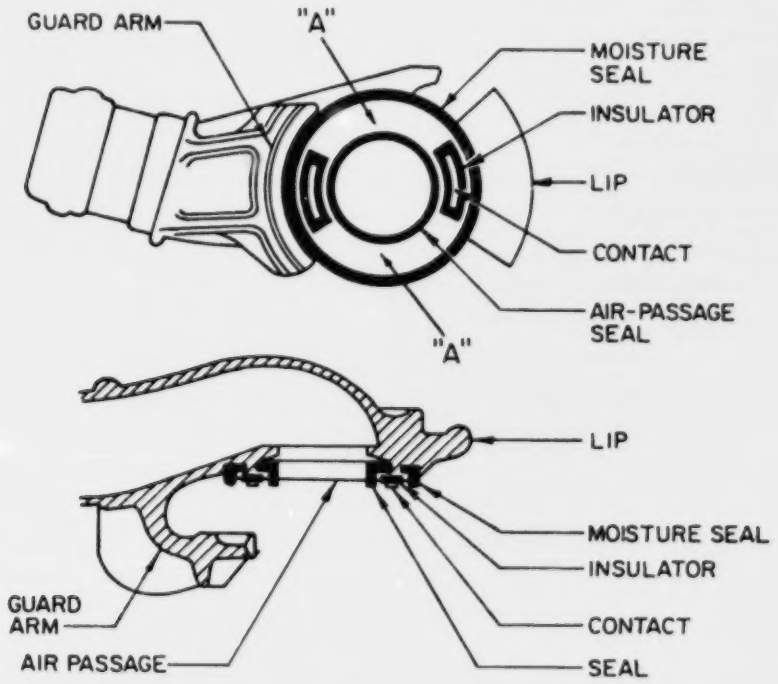



Figure 7.3 An air-electric connector based on the conventional glad-hand air-hose connector. Contacts could also be placed at the positions indicated by "A". This figure is intended to illustrate a concept and is not a fully engineered design.

polarity would be preserved throughout the transmission line. An outer lip provides a weatherproof seal for the contacts when two connectors are mated. It is not apparent, however, how the contacts could be protected when unmated except by some form of mechanical shutter which would likely be susceptible to jamming in ice conditions and vulnerable to damage. Dirt build-up on the contact could be a problem.

Another possibility is to use the body of the glad-hand air-hose connector itself as the contact. Such a scheme is proposed is U.S. Patent No. 3,895,850 assigned to General Signal Corp., Rochester, N.Y., and issued 22 July 1975. In the patent description it is proposed that the glad-hand be cast of manganese bronze instead of the usual ferrous metal to improve the electrical contact and provide a corrosion-resistant surface. The glad-hand provides only one conducting path. The return path consists of two parallel circuits, one through the draft coupler and the other through the wheels and rail. While it is claimed that the two paths provide an adequately low impedance for communications, the reliability of such a path for data or broadband signals is highly questionable.

The principle of the interconnection system proposed for assuring reliable electrical contact when a hose is attached to the angle cock may be of interest in other glad-hand-based configurations. A standard angle cock is modified to house a junction box and an insulated annular contact around the threaded air passage. The air-hose fitting contains a similar annular contact. A face-to-face abutment of the two annular contacts occurs when the air-hose is threaded into the angle cock. Concentric contacts could be employed to achieve two conducting paths.

The tremendous potential of an air-electric connector makes this concept worthy of further study. Refinement of the contact design and the use of appropriate materials such as gold plating, as described in Section 7.1.6, could conceivably make this concept viable.

### 7.1.6 Contact Technology

The basic requirements of a good contact are corrosion and tarnish resistant metal, pressure, wiping action, and adequate contact area for the desired current.[7.17-7.20] Pins and sockets are the most common means of achieving the latter three requirements, and the technology in

this area is very highly developed. Pressure flattens the asperities, or microscopic peaks, on the metal surface to increase the contact area and provide a low resistance path. Contact resistance can be increased by oxide layers, oil films and similar surface contaminants which prevent metal-to-metal contact. The minimum resistance achievable depends on a complex interaction of factors such as the surface finish, contact pressure, oxide-formation properties of the metal, and its physical characteristics. Wiping action is important in cleaning the contact surface and breaking through oxide layers. Gold is often considered the ultimate contact material, especially when there is a strong possibility of contamination in the environment. It is an excellent conductor, has the lowest contact resistance, and does not form oxide or corrosion films. However, gold plating must be relatively thick, about 2.5 microns (100 microinches), and consequently quite expensive, if a truly inert contact surface is to be obtained. When the gold film is too thin, the base metal underlying it may migrate through the pores in the gold and produce a detrimental corrosion product on the surface.

Gold is of no value in arcing contacts where it erodes rapidly and has a strong tendency to weld. Sliding wear characteristics are poor because it tends to gall, smear and wear off quickly. The virtue of gold is that it does not react with other substances, and is unique among metals in this respect. No other metal, even platinum and rhodium, is as completely free of oxide films. Thus, gold contact surfaces provide true metal-to-metal contact with the lowest possible contact pressure under virtually all environmental conditions. The only worry is foreign materials such as dust, polymer films (from insulating material) or grease on the surfaces. Gold is the ideal contact material for connectors intended to handle very low-level signals and requiring contact forces of less than 100 grams.

Gold over nickel is the most widely used gold-plating combination because it provides the surface characteristics of gold, while the hard underplating of nickel prevents migration of the base metal, usually copper, through the pores in the gold. In recent years, this technique has permitted very thin layers of gold to be used, with a consequent cost saving. Gold layers as thin as 0.4 microns (15 microinches) have been used, compared to the 1.2 to 2.5 microns (50 to 100 microinches) normally needed to prevent base-metal diffusion. Furthermore, the use

of a hard nickel underplating creates a hard working surface which compensates for the softness of gold, reduces wear and fretting, and significantly increases the useful life of the contact.

In summary, modern connector design uses gold-plating on contacts designed to operate where there is a high probability of environmental contamination and where signal levels are too low to create voltages sufficient to puncture or break down oxide layers. Because a metal-to-metal contact is obtained with very little contact pressure, connectors designed to require low insertion forces use gold contacts. Such contacts can be designed to withstand very large numbers of insertion/withdrawal cycles without deterioration in performance, despite the poor wear properties of gold. The reason for the apparent contradiction is that highly reliable performance is achieved with forces sufficiently small to produce neglibile wear.

Silver is a general-purpose plating for power contacts. It does not corrode at normal temperatures, but forms a tarnish (sulphide) layer when exposed to atmospheres containing $H_2S$ and other sulphur compounds. Industrial atmospheres are particularly bad in this respect. Although this coating is undesirable in low-level circuits, it is not usually a problem in heavy-current circuits (more than 10 A). Silver contacts usually have sliding action and high contact forces to ensure reliable connections.

Nickel has good corrosion resistance compared to copper and zinc, but is not as good a conductor as gold, silver and copper. It is a hard metal and has good wear resistance. However, its primary use in modern connectors is as a barrier undercoat, as already described above. Nickel barriers not only greatly reduce the migation of base metals, by a factor of over 10,000 times, it also serves as a barrier to the formation of copper sulphides which can also migrate through porous gold layers and creep onto the surface of gold to create a surface film.

About 1980, when gold prices were at an all-time high, there was considerable interest in palladium and palladium compounds as substitutes for gold. A number of new problems not experienced with gold were reported such as tarnish films, the formation of friction polymers, erratic wear characteristics, and a tendency to form microcracks when

plated. More recently, Dupont-Berg Electronics[7.21] and AMP Incorporated[7.22] have each developed nickel-palladium-gold platings which use the palladium as an additional barrier and underlayer. Extremely thin gold "flashes" are used as the contact surface. Dupont-Berg claims that its product is superior to gold in porosity, solderability, bend ductility and wear resistance. In one series of tests, unmated contacts were exposed to a corrosive atmosphere of chlorine and sulphides to simulate five years of field exposure. The test contacts were plated with 0.75 microns of gold, 0.75 microns of nickel-palladium and 0.75 microns of nickel-palladium with a gold flash. On reconnection to a reference receptacle, the contact resistance was measured. The results of this test are shown in Figure 7.4 where it can be seen that the nickel-palladium-gold (Pd-Ni+Au) always has the lowest contact resistance after exposure. In general, both AMP and Dupont-Berg have found that the nickel-palladium underplating with a very thin gold layer performs as well as, and in some respects better

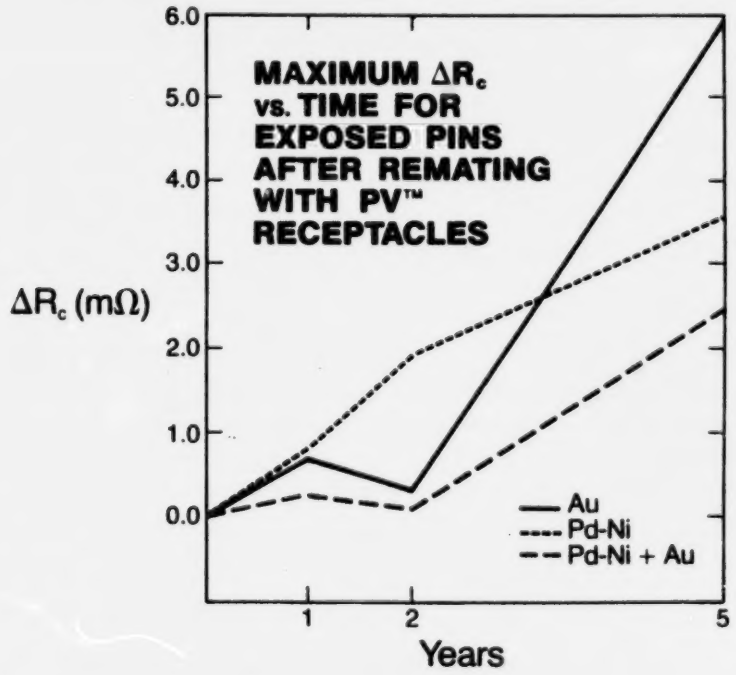



Figure 7.4 Change in contact resistance on remating as a function of exposure time for three platings. (From reference 7.21)

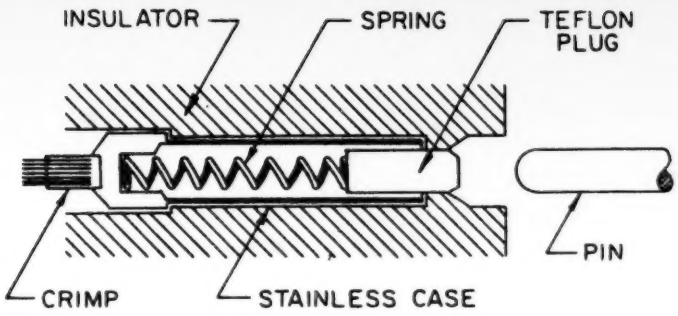
than, thicker layers of gold. The significance of these developments is that contact performance superior to that of gold, including good wear characteristics, may eventually be possible at a lower price than gold plating.

Many connectors designed for harsh environments have used gold-plating on beryllium-copper, phosophor-bronze or brass. But, as mentioned previously, the gold layer must be sufficiently thick that no pores exist through which the base material can migrate and that, today, means high cost. In a recently developed connector series for ship-board applications, Plessey[7.23] has used gold on nickel, as described earlier, which they claim ensures optimum durability and corrosion resistance. However, the Pyle-National C-Line connector, also intended for the sea environment, employs brass and stainless steel in the electrical components.

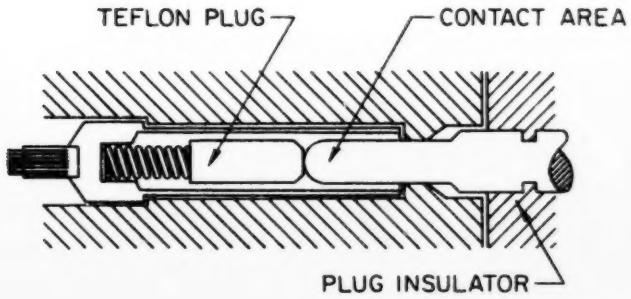
Connector manufacturers consulted were of the consensus that corrosion resistance was not a problem, and that reliable contacts could be assured with silver plating. The Pyle-National TransPower[7.10] connector and the butt or stub connectors used on rapid-transit vehicles are silver-plated. The Amphenol-Tuckel series C158 connector, designed to meet UIC specifications, uses nickel-plated pins and silver-plated sockets. Their connector for incorporation into automatic couplers uses nickel-plated contacts.[7.12]

While exposure to the atmosphere will not degrade the performance of a properly-designed contact, to ensure high reliability under conditions of dirt, dust, dampness and freezing temperatures, contacts should be covered when not in use. Two standard methods of covering contacts are the hinged spring-loaded lid described in 7.4 and the screw-on cap which must be secured by a chain to be sure it will be available when needed. The latter is rejected for the same reason that the threaded connector coupling is rejected. Furthermore, it is too vulnerable to damage or loss.

A novel closure technique has been developed by Pyle-National to keep salt water out of the sockets of the C-line connector.[7.13] In their scheme a teflon, spring-loaded plug within the socket closes the entrance through which the pin must pass to make contact. See Figure 7.5. When connection is made, the plug is pushed along the socket by




(a) CLOSED




(b) MATED

Figure 7.5 The socket closing technique used in the C-line connector. (a) The socket is sealed by the spring-loaded teflon plug. (b) Contact pin inserted.

the entering pin. The spring moves the plug back into the sealed position as the pin is withdrawn. This scheme seems susceptible to jamming by trapped moisture freezing inside the socket. The manufacturer claims that this has not been a problem because water leakage is negligible and any moisture inside could not freeze while the units are mated because of the heating of the contact by the current flowing through it. The concept could, in principle, be extended by designing contacts to enhance the heating effect or, if currents are too low, by including a heating element on an auxiliary circuit.

One technique for achieving ruggedness is simply to make the contacts massive. However, large molded-in contacts can require substantial insertion and withdrawal forces which make the connector difficult to use. This problem has been alleviated in some designs by mounting the socket contacts in a cavity slightly larger than the contact so that the socket is free to align itself with the pin. As well as reducing insertion and withdrawal forces, this technique is claimed to reduce the occurrence of deformed contacts due to misalignments.

Modern connector designs protect pins by a sleeve or shroud extension of the connector shell. While the shroud may protect the pins from physical damage, it provides a cavity in which snow and ice could collect when the connectors are left unconnected, and it would make the contact pins difficult to clean. Nevertheless, it seems to be the only simple means of protecting pins against bending or deformation when unconnected.

Another example of modern contact design is found in the VE series by ITT Cannon, intended for transportation applications.[7.24] In these connectors a conventional split-tine socket contact is mounted inside a stainless steel sleeve or shroud which has a well-defined entrance aperture, as shown in Figure 7.6. This assembly, called a closed-entry socket, is held in a cavity well within the socket insulator, which opens to the engaging face through a lead-in passage just large enough

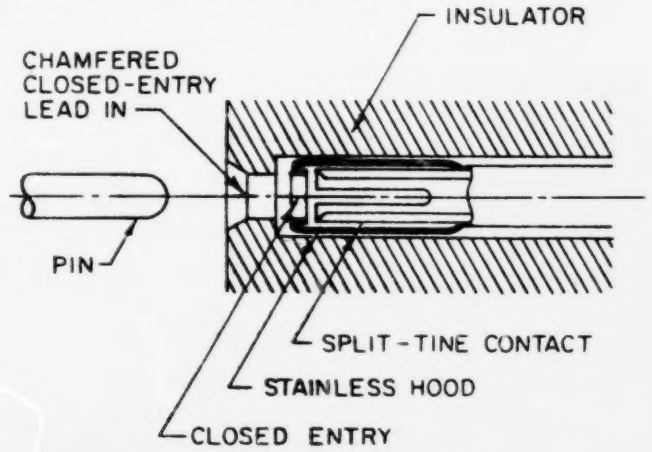



Figure 7.6 The closed-entry socket of the type used in the VE Transportation Series by Cannon ITT.

to allow the pin to enter. A chamfered entrance on the face provides a capture cone for slightly bent pins. The combination of lead-in passage and the opening in the stainless steel shroud assure that bent or misaligned pins will be correctly aligned for proper mating. It is almost impossible for a misaligned, bent or oversized pin to crush or otherwise deform the socket. Furthermore, these design features allow the contacts to withstand prolonged shock and vibration without experiencing permanent deformation. The pins are rounded, bullet-end rods for ruggedness.

The lead-in passage provides some protection from splash and external moisture, but, if moisture in the passages were to freeze, mating would be impossible and it would be difficult to free the passages of the ice. In other words, the socket connectors would have to be covered when not in use. In their present configuration, the VE Series employs bayonet coupling which permits a good environmental seal. Finally, the contact components in this connector are stamped and formed, which means they can be economically produced in large numbers.

Butt or stub contacts have been used in inter-car connectors on rapid-transit vehicles and street cars for over half a century. However, they are a new technology with respect to North American freight-train practice. A butt-contact connector consists of a set of spring-loaded rods which can move longitudinally in sleeves mounted in an insulating block, as illustrated in Figure 7.7. The contact surfaces are the protruding ends of the rods. The connectors are placed at the ends of the vehicles so that when two vehicles are coupled, the ends of the contact rods touch. Contact pressure is achieved as the mechanical coupler binds the two vehicles together tightly. In some systems, wiping action is obtained from the incidental slight relative motion of the contact when the vehicles are moving. Other versions have used a rifled contact rod which rotates in its sleeve as it is depressed by the mating contact. Butt contacts are usually protected by hinged doors when not connected. The doors are automatically opened as the two sets of contacts approach each other in the coupling-up operation. Some installations do not use covers and the contacts are simply left exposed when not in use.

The advantages of the butt contact are (i) ruggedness inherent in its short, thick construction, (ii) no socket to become plugged by dirt,

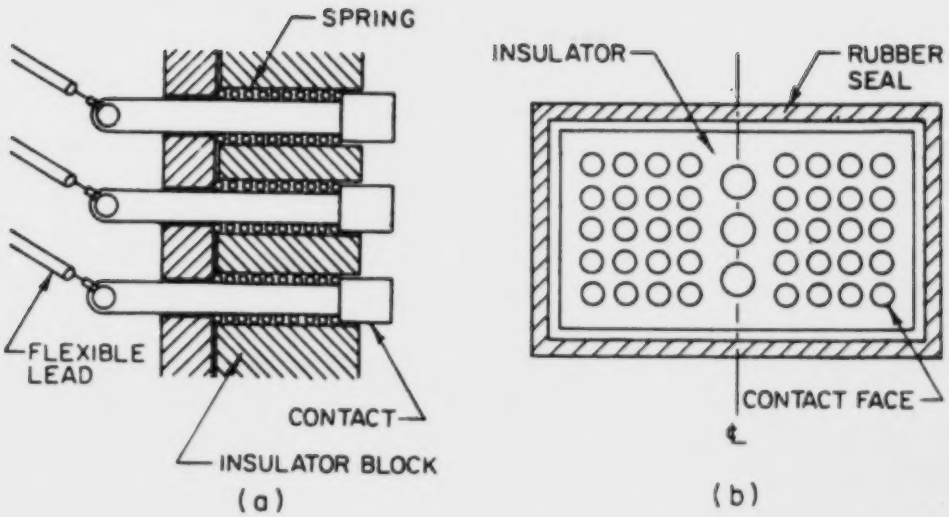



Figure 7.7 An example of the butt-contact mechanism. (a) Cross-section through a row of contacts. (b) Face-on view showing the array of contacts arranged symmetrically about the centre line.

dust and ice, (iii) alignment is not critical, and (iv) the contact surfaces are easily cleaned. Because contact is made by simply butting two rods together "head on," a longitudinal force must be applied. This is not difficult to achieve in the automatic-coupler installation, but could pose a problem for the use of butt contacts in a manual connector. The principal disadvantage identified is that moisture sometimes gets into the sleeve which holds the rod. If this moisture freezes when the contact rods are depressed, that is when the connectors are coupled, the contact will be fixed in the depressed position. This has two consequences: (i) because the spring-loading on the contacts is not forcing them in an outward direction, continuity may be interrupted by vibration and relative motion of the vehicles, and (ii) when uncoupled and recoupled to another vehicle, the contacts may not touch, or touch with inadquate pressure to make a good contact. Dresser Industries, in a 1973 automatic coupler patent (Canadian, 923588) claims to have cured this problem by placing an "O" ring around the contact rod just inside the face of the insulator. Nevertheless, this seemingly trivial problem has been of sufficient magnitude in the Canadian climate that it warrants careful study before

these types of contacts are considered for service in the freight environment.

The automatic inter-car connector used by the Westinghouse Air Brake Company (WABCO) in its rapid-transit installations is similar in housing, mounting and butt coupling to the stub-contact systems described above; however, it employs a distinctly different contact technique. These contacts have been developed by Anderson Power Products[7.14] and are illustrated in Figure 7.8. As can be seen in the figure, two identical contacts will mate if one is turned 180° about its axis. In addition to being inherently hermaphroditic, they are stackable by means of dovetails molded into the insulator housing. The contact itself is silver-plated copper with contact pressure

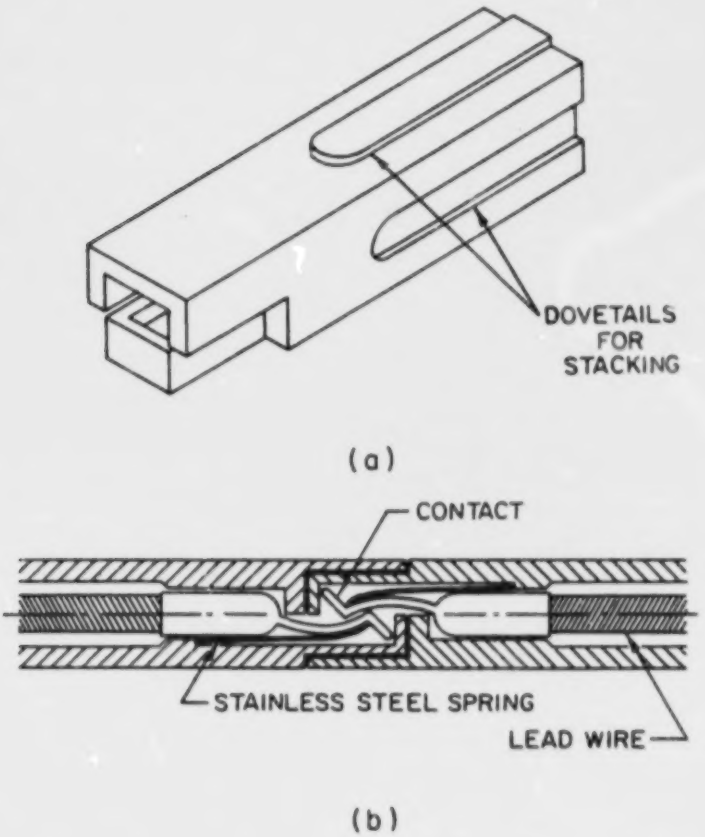



Figure 7.8 Hermaphroditic contact by Anderson Power Products. (a) The Housing for one contact. (b) Two mated contacts.

provided by a stainless-steel spring. Each contact is completely enclosed by a polycarbonate housing, except for the opening through which contact is made. Thus, the contact element is protected and the possibility of shock from accidentally touching the contacts is small. A potential problem with the enclosed contact is that moisture and dirt, once established inside, may be difficult to remove. In the rapid transit application, a door is usually provided to cover the array of stacked contacts.

The series of contacts, called Powerpole, have maximum current-carrying capacities of from 15 to 165 Amps. They are intended for frequent insertion and extraction. Wiping action on make-and-break keeps contacts clean, according to the manufacturer, while the detent in the contact maintains mating until breaking occurs with a quick snap action. The non-conducting lip at the edge of the opening tends to confine arcing if the contact breaks under load. Operating voltage is 600 V.

General Electric's Lexan polycarbonate, from which the insulated housing is made, has high impact strength and gives a uniform molded product. An early problem arose from the use of a solvent sprayed on the contacts to remove the silver oxide. Stress cracks developed which led to a deterioration of the housing. When the use of the solvent, which was not necessary anyway because of the wiping action, was discontinued the problem was eliminated.

If a simple covering system could be devised for this type of contact, it would be a candidate for general railway use in either a manual or an automatic intercar connector.

In automatic-connector patents granted to Dresser Industries in 1971 (Canada, 881129) and to Ohio Brass in 1969 (Canadian, 810506), protection of the contacts is achieved by mechanically pulling the contacts into recesses in a protective housing when the couplers are disengaged, and pushing them forward into contact when the couplers engage. In one case a hydraulic system is used, in the other air pressure. Connectors of this type depend on the mechanical coupling system of the automatic coupler to hold them together in proper alignment. However, they suggest another means of protecting pin contacts. A connector would have pins recessed in shafts in the insulator when not engaged.

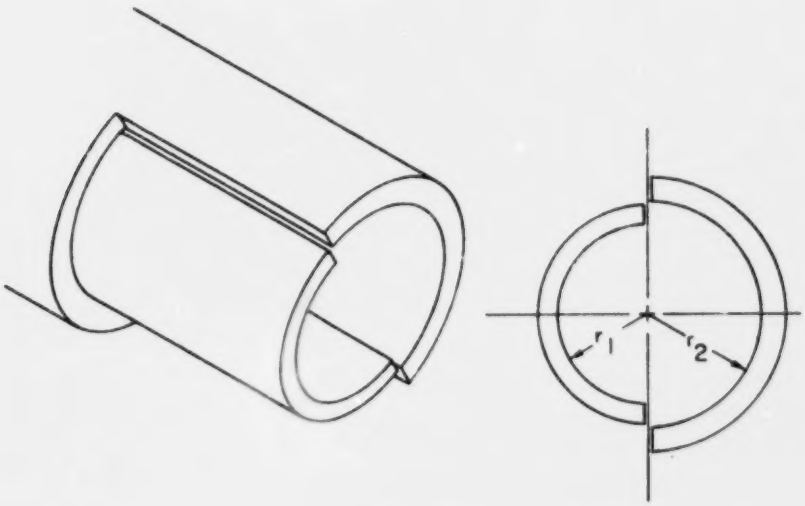
When engaged, the connectors would be aligned by shell shape or keyway and would be held together by the latching arrangement. Then air pressure acting on a piston within the connector would drive the contacts together and hold them in place. Return to the recesses would occur by spring action if the pressure were released. The advantages of such a scheme are the protection of the pins from damage and exposure, and the exertion of the engagement force by the pneumatic system. The latter would permit quick connection. Disadvantages are that if the air pressure fails, the electrical system would disengage, and there are the potential problems of the mechanical system which must move the contacts.

### 7.1.7 Hermaphroditic Requirement

The coupling of freight cars must be independent of the orientation of the cars in the train consist. This means that the electrical connection system must be the same on both ends of the cars. Connectors which are identical and yet can interconnect are called "hermaphroditic" or sexless. Hermaphroditic pin-and-socket configurations can be realized by placing the pins and sockets in mirrored symmetry on opposite sides of a vertical axis. This principle has been used by ITT Cannon in their Geophysical Series[7.25] and by Tuckel in one of its pin-and-socket inter-car train connectors for use on automatic couplers. Butt contacts and the Anderson Powerpole are inherently hermaphroditic.

The principal problem introduced by the hermaphroditic requirement appears to be with the shell, or housing, and the coupling mechanism. Since the connectors must be identical, one shell cannot slide inside the other to provide an environmental seal. If the shell has a slightly smaller radius on one side of the line of symmetry of the contact arrangement, two identical shells will slide together when facing each other, as shown in Figure 7.9. While such a scheme will provide mechanical support, the shells must have longitudinal slits where they change radius, and this could make it difficult to achieve a good seal against moisture. One solution would be integral outer sleeves with end gaskets which would simply butt together when the structural shells are fully inserted into each other. General Radio Corporation manufactured a coaxial connector based on a twofold adaptation of this idea in which there were two opposite 90° segments

with the larger radius and two with a smaller radius. The principal was applied to both the inner and outer conductor of the coaxial connector. Designed primarily for laboratory use, the connectors were not suitable for exterior installations unless they were covered with a protective sleeve. They tended to be fragile, although a heavier, more rugged version could be built. Another example of interlocking shells with longitudinal slits is seen in the hermaphroditic Anderson Powerpole contacts. In this case the shell cross-section is square.




(a)

(b)

Figure 7.9 (a) Illustrating the principle of the hermaphroditic connector shell.
(b) End view of the configuration used in the hermaphroditic coaxial connectors by General Radio.

If the open ends of the connector shells are simply fitted with gaskets, the coupling mechanism must hold the units together with sufficient pressure on the gasket faces to ensure a seal. As is customary on connectors sealed against the environment, the Cannon Geophysical series uses the considerable mechanical advantage offered by threaded coupling to make a good seal against elastomer "O" rings. Pressure on the sealing gasket in the butt-contact, inter-car connectors is provided by the mechanical coupler.

An already familiar technique for assuring universal coupling regardless of car orientation is to install connectors of the same sex at both ends of the cars and couple by means of jumper cables. This involves a component, the jumper cable, which is not attached to the cars and which must be available at the moment and the place that the connection is to be made. A system based on inter-car jumpers would entail much more handling of equipment and introduce twice as many junctions in the electrical path as would a system employing a single connector pair between cars. The advantages of the jumper cable are that existing, latch-cover receptacles could be used on the vehicles, giving quick-connect/pull-apart and a rugged coupling system. Damaged jumper cables can be quickly replaced and sent to a shop for repairs without interfering with train assembly. However, reported experience with jumper cables on passenger trains is not encouraging. Cables are often tossed into the snow or mud, and later reconnected while wet or packed with snow. Connector damage occurs frequently.

By mounting a cable and a receptacle on both ends of every car, say on either side of the drawbar coupler as shown in Figure 7.10, the main advantages of the jumper cable can be retained without some of its disadvantages. When two cars are coupled, each cable will be opposite a receptacle. The parallel paths would provide redundancy, or a loop circuit for self-checking of the link. Cables would always be available on the cars. Engagement of a connector to a fixed receptacle mounted on a car is much easier than joining a pair attached to the ends of cables. Receptacles can be mounted at convenient heights in order to facilitate coupling and minimize the exposure of workers to injury from reaching under and around drawbar assembles. While, like the jumper cable, there would be two connections to be made in every coupling operation the connections are in parallel and can be used to increase reliability.

Any connection scheme using the "glad-hand" principle will be hermophroditic.

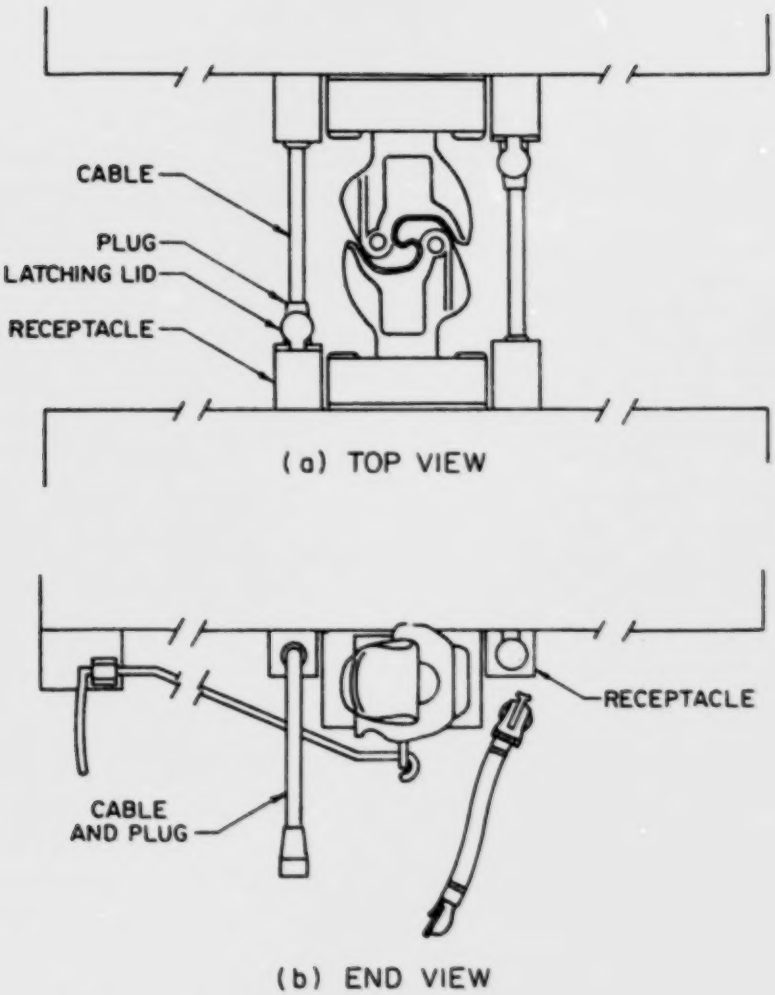



Figure 7.10 Tandem connectors as shown can meet the proposed requirements with existing technologies. The cables would be long enough to provide slack so that the plugs would not be pulled out on curves.

### 7.1.8 Electromagnetic Interference

External electromagnetic (EM) fields can induce currents in the conductors of a transmission line under certain conditions. With a pair of parallel conductors, the coupling of EM fields increases as the conductor separation, measured in wavelengths, increases. Thus, for a given inter-conductor distance, coupling into and radiation from the transmission line increases with decreasing wavelength (higher frequencies). A serious interference problem arises when the parallel conductors are not symmetrically placed with respect to their surroundings. It is essential that the transmission line have a conducting outer shield to ensure symmetrical disposition to a reference potential and to short circuit the external fields. Because the fields are confined within the outer conductor of a coaxial line, it is self-shielding. However, because signal currents flow on the inner surface of the outer conductor, any openings in the shield will tend to radiate and couple to external fields. This phenomenon becomes more important as the wavelength decreases. Complete shielding requires a solid conductor or a very tightly woven braid.

The Office of Research and Experiment (ORE) of the UIC conducted a series of experiments to study the interference voltages on the transmission circuits proposed for the automatic coupler system.[7.26] Two transmission lines were investigated: the loudspeaker cable on passenger coaches and an information circuit incorporated into the coupler. Test runs were made in France, Italy and West Germany using locomotives from the railways of each country (SNCF, FS and DB). A total of nine different locomotives, only one of which was diesel, and four different electric traction systems were involved. Trains consisted of 12 to 16 passenger cars and one or two instrumentation vehicles. Train lengths were from 356 to 439 m.

Measurements of longitudinally and transversely induced voltages were measured and their sources deduced. Experimental digital data was transmitted directly without modems at 48,000 bps and with modems using a 1,700 Hz carrier frequency at 1,200 bps. A CCITT 511-bit pseudo-random test text was transmitted. A further set of digital-data transmission studies was made on the DB trains with a simple "telegram" which permitted the identification of the nature of the errors

occurring in the digital data. This transmission used a carrier of 39 kHz and pulse duration modulation (PDM) at a 600 bps rate.

The results were as follows:

(1) Interference levels rose from 10 to 20 kHz, but significant differences were not observed from 20 to 150 KHz, the upper limit of the measurement.

(2) Signal-to-noise ratios and transmission error rates were about 20 dB lower on the loudspeaker cable than on the information circuit. The considerable difference in quality of performance is attributed to the difference in grounding systems. The shield of the information line is grounded to the body of each car and is not continuous through the automatic coupler. In contrast, the shield of the loudspeaker line is not grounded to the cars and is continuous through its connectors. Best performance is obtained when the lines are terminated symmetrically, i.e. balanced with respect to ground potential.

(3) Longitudinal interference voltages as high as 50 volts peak and transverse voltages as high as 40 volts peak were observed.

(4) With signal levels above 1 mW, a digital data transmission rate of about $10^{-5}$ should be attainable with a transmission line of the type used for the loudspeaker circuits.

The causes of interference identified were switching operations on the locomotive, starting or accelerating, braking operations using the electro-pneumatic brakes, and the periodic switching of the electric heating on and off.

It is clear that continuity of the shielding through the connector will be important in an information transmitting system. Some of the connector designs discussed earlier have been intended for power transmission and may not lend themselves to enclosure in a conducting shield. In general, receptacle and connector housings constructed of metal will provide shielding. What is important is that a good electrical contact exist between the ends of the shields that terminate at the connector. If the connector housing or coupling design does not

permit enclosing shields to come in contact, reasonable immunity to interference should be achieved if the contacts and conductors in the exposed area are close together compared to wavelength, symmetrically disposed with respect to neighbouring conducting material, and shield continuity is maintained by one of the contact paths in the connector.

Increasing concern about the proliferation of stray radio-frequency energy and the interference it causes around circuits operating at low signal levels has led to the creation of a new type of connector called the filtered connector.[7.27,7.28] These devices have an integral radio-frequency filter designed into the connector structure. While the techniques developed are for multi-pin connectors in electronic equipment, the concept would be useful in reducing EMI affecting on-board communications lines. A bandpass filter would be placed as close to the connector as possible, or within it, to trap any pickup of signals lying outside the filter passband. The passband of the filter need be just wide enough to pass the desired signals. In addition to trapping pickup at the connectors, it would also help to eliminate pickups on cars where the shielding is faulty. Such filtering will also reduce the effect of impulse noise. A sharp impulse, as occurs in switching, has its energy distributed over a broad spectrum, much of which will not be transmitted by the bandpass filter.

### 7.1.9 Forces and Vibration

It has been mentioned that contact force is an important factor in assuring good metal-to-metal contact with non-noble metals. However, high forces normal to the contact surface are accompanied by high insertion and withdrawal forces unless a mechanical system is used to press the contacts together after connection. Insertion and withdrawal forces also increase with the number of contacts used. The maximum acceptable insertion/withdrawal force is determined by what an individual worker can exert. Also tied indirectly to these forces is the time needed to make or break the connection. If much tugging, pushing and wiggling is necessary, interconnection will be quite time-consuming as well as producing a high annoyance level in the worker. For connections to a receptacle mounted on a solid massive object such as a car, a worker could manage a 30 kg force (66 lb). If the connection is between two connectors hanging on the ends of flexible cables, the force required should be less than 20 kg force (44 lb).

Lower values are preferable because they would allow faster connection. Account must be taken of the fact that these forces must be applied many times in a relatively short interval during the assembly of a long train.

One advantage of multiplexing data comes into play here. By transmitting all signals on a single pair of conductors, the number of contacts and, hence the insertion forces, can be kept to a minimum. In principle, power and signals can be transmitted on two conductors.

Engagement forces for some of the connectors already mentioned are: Pyle Transpower, 26 kg (58 lb) with three large and three small contacts; Amphenol-Tuckel C158 Series, typically 14 kg (31 lb) with eight contacts; and the 15-30 Amp Anderson Powerpole, 1.8 kg (4 lb) per contact.

Connectors subject to vibration or regular mechanical shocks often suffer from contact fretting wear and, in the case of non-noble metals, fretting corrosion. Some authors claim this to be the commonest source of contact failure. Fretting is caused by small, often microscopic, relative motion of the contacts. Small fragments of the contact material collect between the contacts and on corroding greatly increase the contact resistance.[7.9] To get fretting it is necessary to have relative motion of the contacts. If the forces acting on the contact do not exceed the retention force, no motion will occur.[7.29] Thus, retention forces or, equivalently, the force required to withdraw the contacts, must be greater than the product of the mass of the contact and the highest accelerations expected due to vibration. It appears to have been only in 1981 that the full significance of contact mass in the fretting phenomenon was realized. Low mass contacts and high retention forces are the key to vibration-resistant connectors.

### 7.1.10 C-Line Connector

The Pyle National C-Line connector, developed for marine and hostile environments, is of a sufficiently novel design incorporating features of potential value to a railway connector that it warrants further description here. In fact, Pyle National has already developed a railway version for use on Auto-Train cars. Details of the extensive durability, ruggedness and environmental tests made on the C-Line

connector and information on the Auto-Train version are summarized below.

The coupling mechanism using latching pawls, which are pushed aside as the plug is inserted, has already been described in Section 7.1.5, and the self-sealing socket has been described in Section 7.1.6. The receptacle described comes in a simple flange-mounted version and a junction-box with interlocking breaker which prevents mating and unmating when the circuit is energized. The interlocking principle would interfere with the pull-apart requirement; therefore, it is the flange-mounted receptacle that is of interest. In addition to the receptacles described, which are intended for mounting on a solid structure, there is an in-line or cable-end version employing a more streamlined latch operated by thumb action.

Receptacles are made of fibre-reinforced polyester and plugs are made of Dupont Tefzel which makes the connectors shatterproof even at -60°F. The connectors are rated at 30 amps, 480 V and are three-pole, four-wire polarized devices.

Results of extensive performance tests are as follows:

> Corrosion/salt spray: Unmated specimens subjected to 24 hours of 20 per cent salt spray. No exposure of base metal or dielectric breakdown at 5,000 V.
>
> Thermal shock: No evidence of material cracking, fracture or other damage after connectors being subjected to three hours at -40°C, then 16 hours at 93°C, followed by a further three hours at -40°C.
>
> Water immersion: Wired unmated connectors were immersed for 20 hours in 15 cm of water, subsequently tested at 5,000 V for one minute with no dielectric breakdown.
>
> Short circuit/destructon: Plugs were filled with a 5 per cent salt water solution and mated, subjected to 480 V and 120 Amps corresponding to a locked rotor condition (power factor 0.4-0.5). Other than a slight discolouration, no damage and connectors could be reused.

Contact abuse: Socket contacts withstood probes simulating entry by misaligned pins with no degradation of mating-wiping action.

Drop test: The plug assembly withstood a 4 m drop to a steel plate without damage.

Whip test: A plug on a line was whipped through a 1.4 m arc in a chopping manner against the corner of a steel plate with the full strength that an average man can enforce. Repeated twice. Two small indentations, plug mated with receptacle, no adverse effects.

Crushing: No fracture or distruction to junction-box receptacle under a 2,300 kg (5,000 lb) load.

Icing: Junction-box receptacle mated with plug was subjected to water spray for four hours in a cold chamber. Ice was removed with screwdriver and hammer. Interlock system operated freely afterward. Latches with additional openings to facilitate ice removal have had ice cleared without difficulty. (Also repeated with plug not mated.)

Current rupture: No contact burning or pitting and no electrical or mechanical failure when connector was subjected to 250 cycles of engagement and separation under 150 per cent rated load.

The Auto-Train version has been subjected to a durability test involving 5,000 mating-unmating cycles in which contact resistance, engagement and disengagement forces and contact wear were monitored. The separation operation included the free fall of the connectors after pull-apart disengagement. These connectors were designed to pull apart automatically with car separation. Connector performance was satisfactory for the 5,000 cycles. Some galling of one contact began after 2,000 cycles but contact performance was not degraded. The key-way wear was also monitored with no significant degradation noted. Engagement and disengagement forces were 32 kg (70 lb) and 28 kg (62 lb), respectively, at the start, and 22 kg (48 lb) and 30 kg (65 lb) at the end of 5,000 cycles. Temperature rise was 32°C above an ambient temperature of 24°C and stable.

### 7.1.11 Other Aspects

The voltage, current and bandwidth requirements should not be difficult to achieve with current connector technology. Temperature range should not pose a problem either; however, it is interesting to note that the Amphenol-Tuckel transportation connectors are specified for -25°C to +85°C and the Cannon VE series for -40°C to 105°C, while the Pyle National Trans-Power connector has a range of -49°C to 43°C and the C-line has been tested for -40°C to 93°C. Anderson Power Products claims an operating range of -129°C to 85°C for the Powerpole contacts. The UIC specification is -30°C to 70°C. The range proposed in Section 7.2 is -50°C to 60°C.

In addition to gasket seals and water-repelling dielectrics, another technique used to improve moisture resistance is to increase the dielectric paths between contacts. This is done in the C-line connector by enclosing the pins and sockets in dielectric columns so that the path from exposed metal to exposed metal includes the sides of the columns as well as the direct geometrical distance. In practice, the dielectric path is several times the actual distance between contacts. A potential problem with the dielectric columns is that they will trap snow and, to a lesser extent, dirt. Packed snow within the housing would eventually prevent connection. Covers would eliminate the problem.

Some manufacturers, for example Litton VEAM, supply connectors encased in rubber jackets for protection of the connector against tossed projectiles and to provide greater damping of shock and vibration.

### 7.1.12 Maintenance and Repair

The comments in this section relate to the lifetime expected of the connectors. One approach is to design, if it is possible to do so, a connector which will last twenty years. This will probably involve an expensive connector with a high replacement or repair cost when damaged. Alternatively, an inexpensive connector might serve satisfactorily for a shorter time and simply be discarded when damaged or worn. If the second approach is taken, the connector must be easily changed and there must be a simple, rapid means of identifying a faulty connector.

With micro-electronic equipment on board individual cars, it would be quite straightforward to have a self-checking system under the supervision of the head-end computer. The exact location of a defective connector could be identified.

Another fault detection scheme would have a test box attached at the first car in the consist during assembly of the train. As each additional car is coupled, the test box would know that all was well because the on-board circuits would come alive when interrogated with the continuity-checking code. If no response were received by the test box, it would alert the yardman by means of a radio signal to a "beeper" carried on the yardman's belt.

A cable terminated in a connector would be detachable like the air hose and its connector. That is, the cable would be attached to the car by an environmentally-sealed connector, most likely with threaded coupling, so that in the event of a defect in, or damage to, the cable or inter-car connector, the whole assembly could be quickly removed for repairs and a replacement attached immediately.

An area of connector technology that has received a great deal of attention has been the methods of attaching the lines to the contacts. There are now a number of rapid connection techniques. It is common practice on the better connectors to have replaceable contacts so that damaged ones can be replaced. Such connectors are more expensive than the simpler molded units which would simply be discarded if faulty or damaged.

### 7.1.13 Summary

There do not appear to be any individual connectors on the market which will satisfy the specifications set down in Section 7.1.2. However, there are a number of clever techniques that might be incorporated in whole or in part into a new connector designed specifically for freight-train application.

The two technical problems which must be solved if an acceptable, cable-end, inter-car connection is to be realized are the provision of (i) a hermaphroditic, mechanical coupling mechanism with a good environmental seal, and (ii) a means of covering the contacts of at

least the socket, but preferably of both the socket and plug when disconnected.

At the moment, the only interconnection systems capable of meeting the specifications using existing techniques and components are (i) jumper cables with identical connectors on both ends, and (ii) tandem or parallel cabling in which both ends of the car are outfitted with a cable and a receptable. In both cases, two connectors must be mated to complete each coupling operation.

A possible parallel-cabling system would use a receptacle with latching cover of the type described earlier to house the male contacts. The cable would be terminated in a connector containing female sockets of the self-sealing type used in the C-line connector. In this proposed scheme both sets of contacts are protected when not connected, and hermaphroditic coupling and pull-apart capability are achieved. Obtaining quick-connection will depend to a large extent on insertion forces. A small number of contacts would help keep this low. For example, multiplexed power and signals in principle could be carried by two contacts with a third for shield continuity. If other factors dictate separate power and signal lines, two power contacts, two signal contacts and one for shield continuity would be sufficient. The use of a receptacle with an inserted plug would allow conventional sleeve and gasket moisture-proofing.

Probably the most attractive connector scheme from the point of view of train operations is the air-hose connector with electrical contacts which would permit electrical and air coupling in one operation, as described in Section 7.1.5. This suggestion is purely conceptual at this stage and would have to be developed and refined further before any conclusions could be drawn regarding its viability. However, the potential advantages of such a solution are so great that the idea should not be easily dismissed. A major question that must be answered is whether the contacts would be affected adversely by dirt layers or if there would be sufficiently reliable wiping motion? Nickel-gold contacts which do not corrode or tarnish could be considered. More than one pair of contacts could be accommodated. If contacts were placed on the same arc, circuits might be cross-connected during the rotational motion. Whether this is a problem depends on contact size

and whether or not contacts are alive during connection. Concentrically mounted contacts would avoid this difficulty.

The only automatic coupling scheme considered would take the same form as those used on rapid transit vehicles. It would require fewer contacts and would have to be slung under the drawbar in a floating mount so that it would maintain contact pressure despite longitudinal and vertical motion of the coupler. Initial capture during coupling could be a problem, the solution to which would likely involve a mechanical system susceptible to malfunction in winter and vulnerable to damage. These problems would be added to the problems foreseen with the contact systems as described in Section 7.1.6. "Automatic coupling" by means of contacts on the air-hose connector appears to have greater promise.

An inter-car connector must operate under conditions quite different from those experienced by connectors in conventional applications. For example, most connectors remain connected for relatively long periods of time, whereas the inter-car connector will experience a connect-disconnect duty cycle of about three times per month, and be left unconnected for long intervals in a harsh and abusive environment. Manufacturers' data and evaluations are not directed toward this application; consequently, it is hard to make accurate predictions of the performance and reliability to be expected. It will be necessary to conduct a series of experimental assessments of the most promising ideas to establish how well each would perform in the rail application.

Tests could be conducted on connectors which employ the techniques of interest, even if all of the features of a particular device are not suitable for railway use. For instance, assessment of the contact closure technique in the C-line connector, the Anderson Powerpole in an environment of blowing snow and dust, contacts mounted on "glad-hands" exposed to dirt and an accelerated-aging atmosphere, etc., would help resolve the questions for which no precise answer can be given at the moment. A field test site exists already in the tuned-inductive connector installation on the DAR train in Nova Scotia. This site could be exploited for field studies of other connector types as well.

## 7.2 Fibre Optics

In recent years, fibre optics have proven to be a practical, cost-effective, interference-free communications medium. Fibre-optic links are finding ever-increasing application in telephone distribution systems, electric-power-utility control lines, military environments, cable television services, computer-communciations networks and in the remote collection of data. These varied applications are supported by a dynamic, growing industry which produces cable, light transmitters, detectors and the inter-connection components. The cost of components continues to decline with the increased demand. [7.30, 7.31, 7.32]

An optical fibre is a cylindrical waveguide made of two transparent materials with different indices of refraction. The materials are arranged concentrically to form a core and a cladding layer, the index of refraction of the core being higher than that of the cladding. Glass or plastic may be used for both materials, or they may be used together as a glass core with plastic cladding or vice versa. Light can progagate in the fibre in a number of possible electromagnetic field distributions, called modes, simulateously, or it may propagate in only one field configuration. For practical purposes, a mode is a specific path taken by the light as it propagates. Multi-mode propagation is illustrated in Figures 7.11(a) and (b). Case (a) is an example of propagation in a fibre with an abrupt index of refraction change between core and cladding. Note that a ray making a small angle with respect to the fibre axis travels a shorter path in a given length of fibre, than does a ray making a large angle with the axis. Since the energy of a light pulse is partitioned amongst the modes, and since each mode will take a different amount of time to travel the length of the fibre, an originally sharp, compact pulse will be spread out into a broad, rounded pulse. If the fibre is sufficiently long, the pulses of a digital message may be spread to the point that the "ones" and "zeros" overlap and are indistinguishable. This phenomenon is called modal dispersion. In case (b) the index of refraction changes gradually toward the outer surface of the fibre. The rays taking the paths farthest from the axis are passing through the part of the core that has the highest velocity. Thus, the longer paths are traversed at a higher velocity, on average, and the dispersion is not as severe. This fibre construction is called graded index. Finally, case (c) illustrates single-mode propagation where the only mode that can be

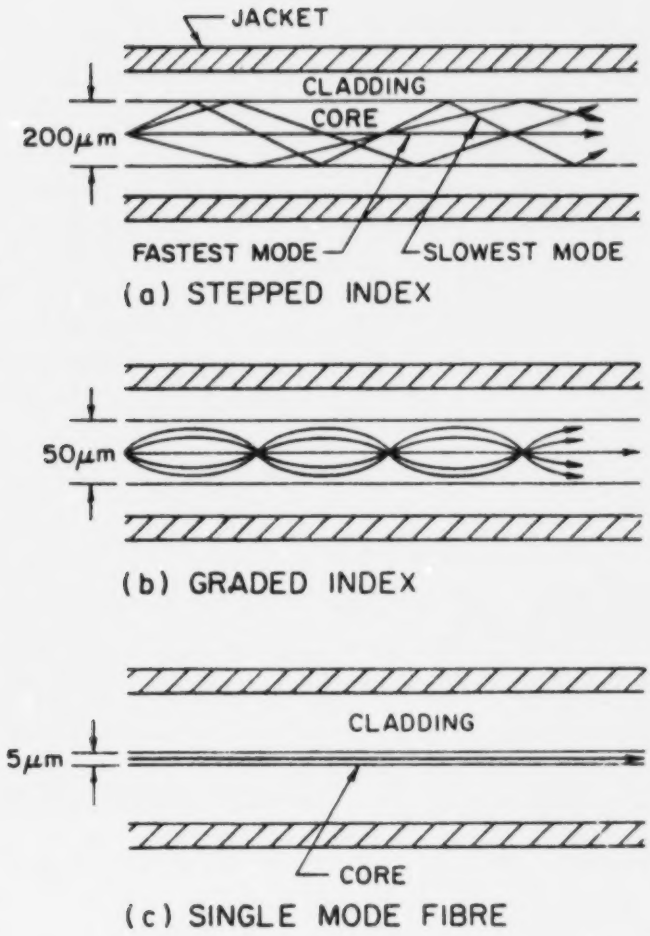



Figure 7.11 Cross-sections of optical fibres illustrating: (a) stepped-index, multi-mode propagation, (b) graded-index multi-mode propagation, and (c) stepped-index single-mode propagation.

sustained and propagated is the one travelling down the axis. Single-mode propagation requires a core of dimensions comparable to the wavelength of the light in the material. Modal disperson is eliminated.

Attenuation in optical fibres is due to scattering by minute density irregularities and adsorption by impurities such as OH molecules and metal ions. Purity of the glass or plastic and the control of the fabrication process determine the attenuation contributed by these sources. The fundamental limit to attenuatation is due to Rayleigh scattering which is inherent in the material. Rayleigh scattering

decreases rapidly with increasing wavelength; for example, doubling the wavelength from 0.8 micron (micrometres) to 1.6 reduces the theoretical lower limit of attenuation by a factor of 16. This is the reason that recent interest has been directed toward single-mode, long-wavelength systems.

At present, graded-index fibres operating at a wavelength of 0.8-0.9 microns have attenuations of the order of 3 to 10 dB/km and offer bandwidths of hundreds of MHz-km (100 MHz in a 1 km length, 50 MHz in a 2 km length, etc.). In the 1.3 to 1.5 micron range attenuation of less than 1 dB/km would be possible. Last year Corning Glass Works reported production of a single mode fibre with 0.16 dB/km attenuation at 1.55 micron. Several fibres are now available with 0.3 to 0.6 dB/km attenuation for use in the 1.3 and 1.55 micron wavelength. An excellent survey of the current state of the technology, including transmitters, receivings, couplers, connectors, etc., can be found in reference 7.31.

Because the distances are short in an on-board communications system, the larger diametre multi-mode fibres would be adequate. These fibres have been in commercial use for several years and the technology is well developed. Also, the matching of sources and detectors is less critical with multi-mode fibres.

Figure 7.12 shows the construction of a practical fibre. A moisture resistant compound next to the glass member is important because moisture can contaminate the glass, causing degradation in performance Mechanical strength is provided by the Kevlar or similar layer. Sometimes steel wires are used for strength. A cable may consist of a number of independent fibre bundles concentrically placed around a strength member. Usually the bundles are wrapped helically around the core so that the cable can flex without creating tensile stresses on the outer radius of the bend.

Lifetimes and ruggedness of electro-optical devices are good. Claims of $10^6$ hours (114 years) at 20°C have been made for lifetimes of light-emitting diodes and semi-conductor lasers. The lifetime decreases by a factor of 10 for operation at 40°C. Fibre lifetimes are estimated to be 20 to 30 years, provided the core and cladding are well protected from contamination and physical damage. Fibres are strong, having tensile strengths comparable to steel wires of the same

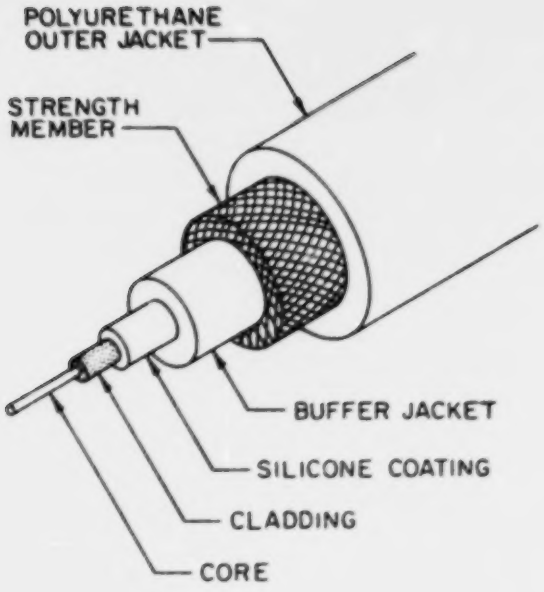



Figure 7.12 Construction of a practical optical-fibre cable

diametre. With good surface quality in fabrication, i.e. no surface flaws, the fibres are capable of withstanding bending and stretching without permanent damage. Information on the physical characteristics of cables has been taken from references 7.31, 7.32, 7.33, 7.34 and 7.35.

The railway companies have recognized the potential of optical fibres for high-density voice, video and data transmission. Field installations by Union Pacific, Canadian Pacific, British Rail, German Federal Railway, SNCF, and some rapid-transit systems have confirmed that optical fibres have much to offer as high-capacity, interference-free communications links in the railway environment.[7.36, 7.37, 7.38, 7.39, 7.30]

While wayside applications of optical fibres are developing rapidly, on-board use has not received nearly as much attention. Fibre-optic communications links on freight trains would have the following merits:

(1) Immunity from electrical interference. The dielectric nature of the glass fibre makes it immune to induced currents from adjacent wiring,

strong electromagnetic fields caused by the interruption of large currents in the motive units, external radio communications and electrical noise generally. Connectors do not have to provide continuity of electrical shielding.

(2) Bandwidth and data rates. The bandwidth of optical fibres is expressed in MHz-km, which means that useful bandwidth is inversely proportional to the length of the fibre. Bandwidths from 100 to 1000 MH-km are readily achieved with current technology. In contrast, the bandwidth of electrical lines is inversely proportional to the square of the line length.

(3) Potentially low cost. Intrinsically expensive materials such as copper or aluminum are not needed. However, a protective covering, most likely in the form of a solid conduit, would be necessary in a freight operation.

(4) Communications are unaffected by surroundings. The fibre optic link provides broadband communications not dependent on line-of-sight paths, and unaffected by wayside equipment, tunnels and terrain.

(5) Electrical safety. Because the optical fibre is an insulator,, there is no danger of shock or short circuit when connectors are wet. Dangerous voltages cannot be induced in long loop paths as happens with metallic cables. This feature is of particular interest on electrified railways. It should be noted, however, that rugged optical cables are often covered by a metal tube or are wrapped in a metal tape over which the outer polyurethane jacket is applied. Because the metal protective layer has nothing to do with signal transmission, induced voltages could easily be trapped and rendered negligible. Cables with non-metallic strength members and non-metallic protective covers would have the advantage of not causing short circuiting of electric conductors in case of accidental damage to the cabling on a car.

(6) Vibration and shock resistance. Optical fibres in military applications have been found to be superior to copper wire from the point of view of fatigue failure and durability in high-vibration environments.

(7) Because they do not radiate signals, they cannot interfere with other services and are not susceptible to regulation.

(8) The optical "contacts" in a fibre optic connector are inherently hermaphroditic.

(9) Fibre-optic cables are constructed of durable non-corrosive materials. Lifetimes of 20 to 30 years are expected.

In many respects, the advantages offered by the optical-fibre link are those of the hard-wired transmission line described in Section 7. The principal additional features are immunity to all external electromagnetic radiation, extremely large bandwidth and electrical safety. The bandwidth and data-rate capability of the optical fibre far exceed the needs of the model defined earlier.

The problems identified in the application of optical fibres to freight train communications are given below:

(1) Every car in the consist must be equipped with an optical-fibre link before benefits can be derived.

(2) While attenuation in the optical fibre can be less than 1 dB/km, the fibre-optic connectors have typically losses of 0.5 to 1.0 dB at best and, under the looser tolerances and contamination expected in the railway application, they may introduce several dB of loss. Such losses would preclude the use of a continuous fibre transmission line running the length of the train. Furthermore, loss of power would occur at each car as light energy is coupled out of the fibre for local detection on the car. Therefore, a practical link configuration would require detection, electronic amplification and retransmission on each car. Two-way information flow would require two such repeaters and either two fibre lines or a duplexing coupler. Access to the informaton flowing in the line would be gained most readily at the electronic amplification stage.

(3) The need for amplification and retransmission at each car introduces a very important fail-safe or default consideration. Failure of the electronic

equipment on one car would block the whole link. In the two on-board fibre optic systems described below, this problem has been circumvented by providing two signal paths.

(4) A highly-reliable, inter-car connector would be needed. Its mechanical and environmental specifications would be essentially the same as those defined for the electric inter-car connector. The problems encountered in meeting these specifications would also be the same. In addition, optical-fibre connections require high precision.

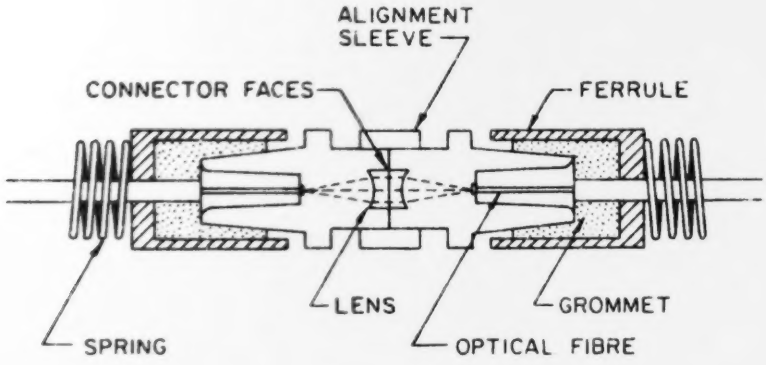
(5) Optical fibres are not capable of delivering enough power to operate electronic equipment on board the car. A source of power will be necessary for the opto-electronic, micro-electronic data-processing, and electro-pneumatic systems.

(6) At the moment many of the features offered by fibre-optic communications are of greatest benefit to high-density telephone or data transmission. For a single channel fibre optics is not considered to be cost-effective compared to a simple twisted pair of copper wires. The cost side of fibre-optic systems will have to be monitored. Rapid changes in the component technology and refinements to the manufacturing techniques are continuing to reduce costs.

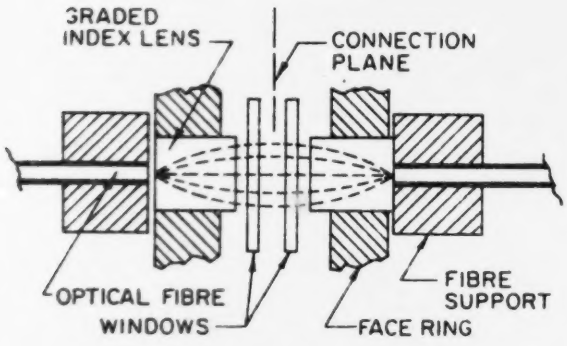
With regard to the inter-car connection, the most interesting concept is the expanded-beam lens-to-lens technique used in the Expanded-Beam-Lens (EBL) fibre-optic connector by GTE.[7.41] Systems employing butt-to-butt contacts of the fibres would be far too susceptible to dirt and would require lateral alignments within microns (1 micron = $10^{-6}$ metres).[7.42] In the EBL connector, shown in Figure 7.13(a), the cross-sectional area of the fibre is expanded 400 times by a lens. On entering the mating unit, the light is focussed onto the end of the fibre where it continues in a fibre-optic propagation mode. The connector is considered to be rugged, and is intended for both commercial and military application. Attenuation through a mated pair is typically 0.7 dB with a maximum of 1.0 dB. Lateral misalignment of 0.14 mm causes a 1 dB increase in attenuation. This is to be compared to a butt-contact connection which suffers 1 dB additional attenuation with only a 0.05 mm lateral misalignment. GTE claims that the connect-disconnect cycle can be repeated 1000 times without significant

variation in connector characteristics. In its present configuration, the connector uses threaded coupling.

TRW Inc. has also recently developed an expanded-beam connector.[7.43] In its version a protective window has been added in front of the lens, as shown in Figure 7.13(b). The connector is intended for military applications and is considered to be physically rugged, submersible, and fungus-, salt-, mud- and vibration-proof. It is coupled by a hermaphroditic, threaded mechanism, has been cycled through -57°C to +71°C temperatures, can be repetitively mated 1,000




(a)




(b)

Figure 7.13 The expanded-beam-lens principle in optical-fibre connectors. (a) GTE version using a molded len. (b) TRW version using a graded-index lens and a protective window.

times and has an attenuation of 1.5 to 3 dB in the preliminary versions at 820 nm wavelength. The lens in this connector is a cylinder with a quadratic refractive index gradient in the radial direction, similar to that of a graded-index fibre.

One of the reasons for expanding the light beam is to reduce the relative importance of dust at the interface. By expanding the beam area 100 or more times, dust specks become two orders of magnitude less critical than they would on the end of a 50 micron fibre. Furthermore, the lens surface can be wiped clean, something that is practically impossible to do with raw fibre ends. Nevertheless, some concern remains for the effect of dirt on the optical transmission path. It would seem advisable to provide an automatic cover to protect the exposed lens when disconnected.

Because of its greater tolerance of misalignment, the EBL principle is potentially capable of good performance in the presence of vibration and mechanical shock. The low mass of the connector elements is also an advantage here. While small relative motions induced by vibration may cause electrical contacts to momentarily interrupt the circuit, the relative motion of the optical contacts will cause the signal level to fluctuate. In other words, the optical circuit experiences a relatively gradual degradation of continuity with small movement, not an abrupt interruption.

There may be a temptation to overcome losses by increasing source power, since many light sources designed for communications applications are capable of delivering tens of milliwatts. In this connection, it should be noted that milliwatts of highly coherent light could be hazardous to the eyes of people working with fibre cables. Light at wavelengths greater than 0.8 microns is not visible. This aspect has to be taken into account in designing the system.

The only known working example of an optical inter-car connector in use is the AEG-Telefunken and Fabeg system currently being tested on the Berlin subway.[7.44] The optical connector is incorporated into the Scharfenberg-FABEG automatic coupler along with the electrical and air connections, and is mounted among the electrical butt contacts. It is designed to couple four optic cables and is capable of handling a data flow greater than 1 Mbps. If one of the optical paths is interrupted,

the system, which is shown in Figure 7.14, automatically switches to another. The lens system, which is similar in principle to the ones described above, is shown in Figure 7.15.

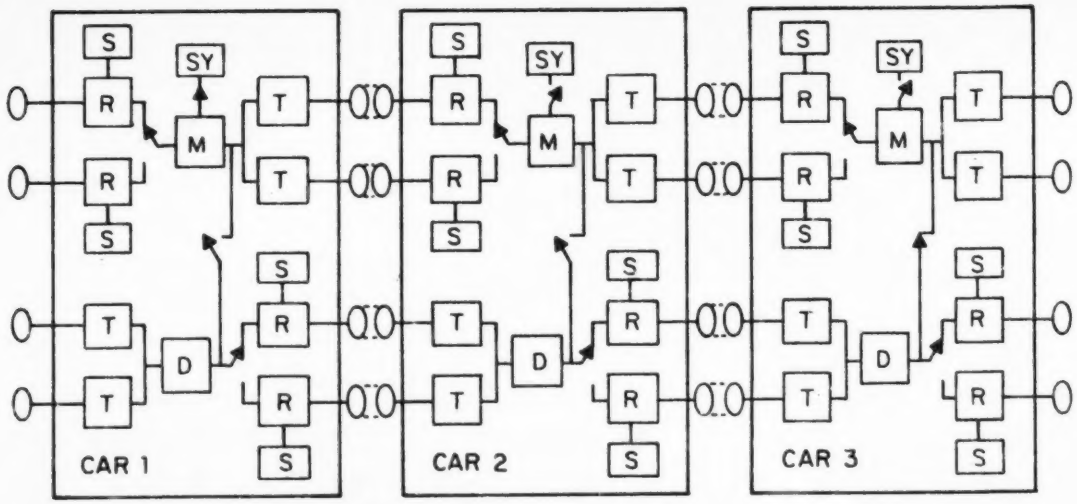



Figure 7.14 The AEG Telefunken and Fabeg optical communications link being tested on the Berlin subway. T = LED transmitter, R = photodiode receiver, M = modulator, D = demodulator, S = monitoring circuit which determines whether the channel is operating properly, SY = clock for data synchronization. (Note that only one is active.)

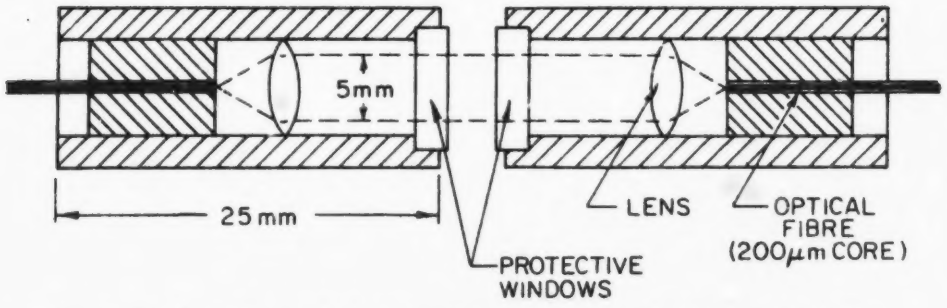



Figure 7.15 Essential elements of the optical "contact," four of which are installed among the electrical contacts of each automatic coupler on the Berlin subway test vehicles.

A proposal for an on-board optical fibre communications system has been made by Hitachi of Japan.[7.45,7.46] In their system the inter-car connection is to be made by a flexible cable and connector between cars. The cable carries four optical fibre cables and ten metallic conductors. The connector, developed by Hitachi and Japan National Railway, couples the optical and electrical circuits simultaneously. Data rates in the communications system are to be 1 to 2 Mbps. The application of this fibre-optic link is to surveillance of equipment, passenger service data, and train-control data on passenger trains.

The optical fibre is of step-index construction with a core diameter of 120 microns and a cladding of 200 microns. Losses at a wavelength of 0.85 microns are 5 dB/km and the bandwidth factor is 15 MHz/km. Attenuation through the jumper cable was measured as a function of the number of bending cycles. Cables were tested to 300,000 flexures, which corresponds to 15 year's use, with less than a 10 per cent change in losses. In coupling-decoupling tests the connector losses increased by different amounts in each of the four fibre contacts; however, the largest increase was only 20 per cent in 500 coupling-decoupling operations. The contacts were cleaned and cycling continued another 500 cycles to a total of 1,000, at which point the attenuation had doubled. Subsequent cleaning left the attenuation at about 20 per cent above the initial value of 1 dB. The connectors are not hermaphroditic, nor do they use the expanded-beam-lens principle.

The transmitter is an LED with a power output of -15 dBm or about 30 W, and a power supply requirement of 5 V at 250 mA. The receiver is a PIN diode requiring a -30 dBm light level. Its power supply requirement is 5 V at 100 mA. This transmitter-receiver combination operates at 9,600 bps with an error rate of less than $10^{-9}$. The operating temperature range is -20°C to 75°C.

To ensure fail-safe operation, a loop is employed in which two fibres provide a two-way signal path which is tapped at each car to exchange information with the car. The other two fibres provide a head-to-tail uninterrupted two-way signal path. Thus, two complete loops running from cab to tail and back are created with signal flow in opposite directions. A signal is launched on both loops simultaneously and arrives at its destination from two directions with a time delay determined by the position of the transmitter and receiver in the train.

The system is intended for a maximum of 20 stations comprising 18 cars and a motorized unit at each end.

Failure rates have been estimated for this system. For 20 stations a failure rate of 100 x $10^{-9}$/hour is expected. This rate is for complete loss of communications, not for partial failures which are accommodated by the loop system without interruption to the service.

Similar combined optic/electric connectors have been developed, for example by Amphenol,[7.47] but the Hitachi unit is the only one identified as designed for railway use. These connectors hold the fibre in pin and socket-like sleeves which mate in the same way as conventional elecric contacts. Correct alignment of the fibres depends on the alignment of the pins in the sockets. Losses of about 3 dB occur with this technique. Threaded coupling is used.

Fibre-optic lines have been used by South African Railways to carry data from sensors at various points in the train to an instrument car. While this application is believe to be a research use to investigate train dynamics, the experience with the optical system has confirmed its superior performance compared to conducting transmission lines from the point of view of electrical interference. The manner of inter-car connection, if any, is not known.

In the two examples of optical jumper cables described above, the connector faces would be well protected. The Hitachi connector uses a threaded coupling indicating that it is likely to be left connected for relatively long periods. The Berlin subway system is built in the Scharfenberg-FABEG coupler which has doors that automatically cover the electrical and optical contacts. An automatic shutter system has been propsed for optical links in the UIC automatic coupler.[7.39] However, the problem with mechanical shutters in the Canadian context would be their susceptibility to jamming in freezing weather. It is inevitable that a dirt layer will form on the faces of the connectors, causing increased attenuation and possibly scratching of the protective window. Claims by the manufacturers of EBL connectors are that they can withstand such treatment, and do in the military applications. Nevertheless, this aspect of fibre-optic connectors would have to be given careful study before a commitment to such a syscem could be made.

With regard to electro-optical hardware, the technology is still evolving with new developments appearing regularly in the research laboratories. In the future many new devices can be expected. Integrated optics, the optical counterpart to integrated circuits, fabricates detectors, light emitters and amplifiers on a single chip. The packaging of a system on a single chip is well established as the key to high reliability. Environmentally resistant packaging would also be facilitated A complete repeater with detector amplifier and semi-conductor laser on a chip has been reported. Another very recent development is a diode device called EROS (emitter-receiver for optical systems) which is able to serve either as an emitting LED or as a receiving photo diode. This capability permits two-way transmission in a single fibre and eliminates the need for a costly optical separator.

In recent months amplification within the fibre itself has been reported. If this became practical, the problems of repeater failure would be eliminated since the fibre would be continuous through the amplifier.

These and other developments auger well for the future. Inexpensive compact hardware will make redundancy to overcome some of the more fundamental problems outlined above more attractive.

Conclusions regarding the use of fibre optics on freight trains are:

(1) Optical fibres have considerable potential as rugged, inexpensive, interference-free links for communications, surveillance and control on freight trains.

(2) An auxiliary power source must be available on board and this means additional high-maintenance items such as generators or batteries will be required, or an electric train line (see Item 3).

(3) The connector problem is no easier for optical fibres than for electric lines. With the expanded-beam technique, it is probably no more difficult either. Protecting the lens from dirt when not connected is a major problem to be solved. The combined optical/electical connector would provide an interference-immune link for communications and control, while power to operate the electronic, electro-optical and

electromechanical systems would be supplied by the electric line.

(4) Connector losses and loss of signal power coupled out at each car preclude optical fibre continuity on long trains. Repeaters will be needed on each car. Because a failure of the repeater would interrupt the link, redundancy or alternate paths must be provided. The possibility of a default system which bypasses the repeater would be an alternative solution, but the practicability of this idea needs to be studied.

(5) On-board equipment will require a more sophisticated technology but not necessarily a more expensive one. However, a sophisticated technology will have important implications for fault detection, repairs and maintenance. Damage to the fibre-optic cable is often unrepairable. In most cases the entire section of cable must be replaced.

(6) The fibre manufacturing and cabling technologies are now well developed. However, the terminal hardware is still evolving with many new products and concepts still at the laboratory stage of development. In the future integrated optics will do for optical hardware what it has done for electronic circuits in providing compact, inexpensive, reliable, ruggedly packaged, complex systems.

## 7.3 Waveguides

Electromagnetic (EM) energy can be transmitted very efficiently through hollow conducting pipes which are usually of rectangular or circular cross-secton. These single-conductor transmission lines, called waveguides, have attenuation factors as much as two orders of magnitude lower than those of coaxial cable and open-wire lines operating at the same frequency. The cross-sectional dimensions of the waveguide must be comparable or greater than half the wavelength of the EM waves to be transmitted by it. Therefore, in practice waveguides are used at high frequencies, that is at short wavelengths (microwaves), where guide dimensions are not impractically large. A 2.5 cm x 5.0 cm (1 x 2 inch) rectangular waveguide will propagate EM waves at frequencies above 3 GHz with an attenuation of about 10 dB/km in the 4 to 5 GHz range.

A circular waveguide of 5 cm diameter operating in the 40 to 100 GHz range can have an attenuation as low as 2 to 3 dB/km. This is because the $TM_{01}$ mode (field configuration) has the unusual property that attenuation decreases with increasing frequency for a given waveguide dimension. The practical problem encountered in using $TM_{01}$ mode is that mode trapping structures are necessary in the guide to ensure that energy from the low-loss mode is not converted into higher-loss modes during propagation.

In the study of freight-train communications media which was carried out in the early 1970s, waveguides were examined in connection with inter-car EM coupling by means of horns. The idea was rejected as impractical because the wavelength would have to have been of the order of millimetres to achieve sufficient directivity in the horn antennas, and at such short wavelengths the attenuation in the waveguide becomes appreciable.

There are a number of undesirable characteristics associated with a waveguide communications system in the railway application. In general waveguides are expensive because of the precise construction required and, in the case of circular guides, the need for internal mode-trapping structures. Signal sources, receivers and coupling hardware generally increase in cost with increasing frequency. Furthermore, the ability to generate power decreases with frequency. It would be quite impractical, and probably impossible at the moment, to generate kilowatt power levels at GHz frequencies. Technology in the high GHz range is still developing. Waveguides are very sensitive to deformations in the guiding surface. Thus, despite the rugged appearance of the "hollow pipe," it would have to be protected. Moisture inside the guides also disturbs propagation. Oxidation of the inner surface will increase attenuation Therefore, the guides would have to be either filled with a dielectric which increases attenuation, or hermetically sealed, or otherwise kept dry. Attenuation, while low compared to other transmission systems operating at the same frequency, is high if the system is to deliver large amounts of power. The power levels needed to supply the on-board equipment would be extremely dangerous to personnel if radiated by accidental opening of the waveguide. At the moment waveguides are considered practical only in communications situations where very large (250,000 circuit) telephone channels are needed.

Despite the negative features of waveguides, there is one waveguide technique that looks relevant to the inter-car connection problem at lower frequencies. Lengths of waveguide and waveguide components are often connected by means of choke flanges.[7.48] These flanges have a quarter-wavelength deep groove cut in the face of the flange, which acts as a trap presenting an infinite impedance to electromagnetic energy trying to migrate outward at the waveguide junction. These flanges are so effective at trapping the EM energy that a slight misalignment of two guides has a negligible effect and flange faces can be as much as 1 cm apart with a loss at the junction of less than 0.05 dB.

A choke flange, with its face covered by a protective plastic coating and fitted with a mechanical coupling mechansim to hold two flanges in contact, would make a potentially rugged, simple, inter-car connector. However, because of the other less attractive properties of waveguides, a lower-frequency coaxial device embodying the same trapping concept might prove more practical. No connector based on this principle has been uncovered. However, the principle is used in "baluns," devices which prevent currents from flowing on the outside of the outer conductor of a coaxial cable when it makes a transition to a two-wire balanced line or an antenna. Even if an efficient connector based on the choke-flange or balun principle could be constructed, it would have to operate at metre wavelengths, i.e. VHF frequencies, where the losses in conventional coaxial cable are significant or low-loss cable is expensive.

The conclusion drawn with regard to waveguides is that they do not represent a practical transmission medium for use on freight trains. The choke-flange or balun principle employed in inter-car coupling would in itself be of interest, but it would lead to an overall system attenuation which would be too high for the transmission of power to operate electronic equipment and electromechanical devices. Such a system could be used for communications and signalling, in which case it would offer MHz bandwidths. Of course, the connector concept has yet to be developed and demonstrated.

## 8. COMMUNICATIONS THROUGH EXTERNAL MEDIA

Four techniques have been identified for communicating between cab and cars by means of transmission media external to the train. These are:

( i) two-way radio directly linking cab and individual cars

( ii) inductive coupling of cab and car signals to a cable running along the roadbed between the rails

(iii) radio-frequency coupling of cab and car signals to a leaky or surface wave transmission line running between or beside the tracks

( iv) two-way radio relayed along the train by means of on-board transponders.

An important feature offered by schemes (i), (ii) and (iii) is independent access to the equipped cars. This means that in-train communications is possible between the cab and those cars outfitted with the communications hardware without requiring all cars in the consist to be equipped. Thus, access to the equipped cars is not hindered by the presence of unequipped cars in the consist, nor would malfunctions or damage on one car shut down the whole system. Benefits can be realized immediately with only partial outfitting of the fleet during the transition period to fully outfitted trains. Scheme (iv) can also accommodate unequipped cars and can by-pass malfunctioning units provided the active transponders have a transmission range of at least several car lengths.

A significant practical advantage common to all of these schemes is that no physical link is needed between cars. Since there would be no additional items to couple during train assembly, labour and skill levels involved would not be affected.

None of these technologies can provide a practical means of transferring power from the cab to the cars at the level required to operate electromechanical circuits. Consequently, the implementaton of any of the links employing only transmission media external to the train will require on-board power sources at the individual cars. If a communications system is to function when the train is at rest as well as when it is in motion a source of stored power such as a battery must be

available. This introduces the need to provide a means of switching of the source when it is not in use. A simple procedure, which detracts from the "no-connection" feature, would be to throw a switch during assembly and break-up of trains. A solution compatible with the advantages offered by these schemes would be a pilot receiver operated by an external long-life, low-power source, which would turn the primary power supply on or off in response to a highly coded initiation signal.

All radio-based links require some means for confirming the continuity of the link. This is normally done by means of "call back" or "handshake" messages from the unit receiving an instruction. Lack of a call-back after some predetermined interval, or after a certain number of repetitions, would result in a switch to an appropriate safe mode, warning signals to the trainman, etc. The inclusion of a call-back protocol increases the data flow above that discussed in the model.

## 8.1 Radio

Radio communication is at a very advanced state of development. Integrated circuit technology has permitted the implementation of sophisticated modulation and coding schemes in small, low-power packages. Examples of existing radio communications systems in the freight environment are:

(i) Two-way voice transceivers (walkie-talkies).

(ii) "Locotrol" which is used to link a "master" locomotive to one or more "slave" units located at different points in the train.[8.1]

(iii) End-of-train units (ETU) developed to replace cabooses and transmit tail-end pressure by radio to the cab as well as indicating that the train is intact. Florida East Coast Railway has had end-of-train monitoring in place for a number of years.[8.2] Glenayre and Union Switch and Signal have developed systems called "Digitair" and "Trailguard," respectively.[8.3,8.4,8.5] Like the FEC units, they provide periodic updating of air-pressure transmitted with identification codes to counter possible interference and assure reliability of data.

( iv) Southern Pacific's brake-fault detector transmits the time of arrival of air-pressure pulses triggered by the accidental functioning of a brake valve. Comparison of the time of arrival at the cab and caboose permits calculation of the position in the train of the faulty brake valve.[8.6]

These examples illustrate the considerable amount of experience with surveillance and control by means of radio communications that already exists in the industry.

Cab-to-car radio links are illustrated schematically in Figure 8.1. The attractive features of radio links are:

(1) no material medium is needed to carry the signals

(2) the technology is well known and well developed

(3) independent access to cars is possible

(4) no coupling-up operations necessary.

(5) direct communications between cars and trackside stations would be possible. This could include other types of monitoring functions such as automatic car identification.

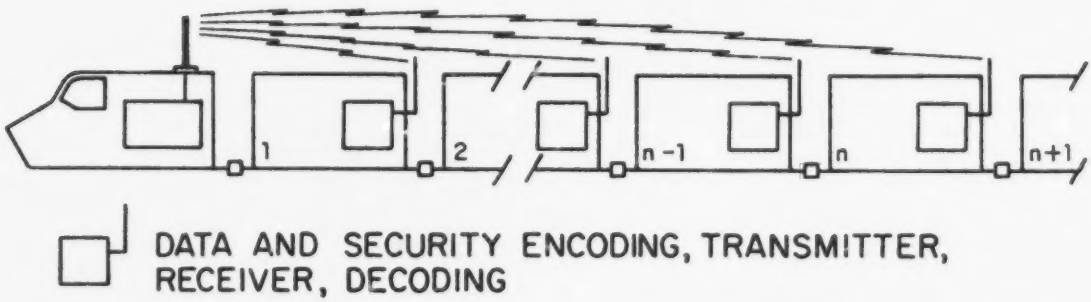



Figure 8.1 A schematic representation of on-board communications by means of independent, cab-to-car radio links

Set against these features are several problems:

(1) Interference. Because the medium is "open," radio communications are susceptible to interference from strong signals in the same or adjacent channels, and from electromagnetic interference (EMI) generally. Sophisticated coding would be needed to ensure reliability.

(2) Propagation reliability. Extensive testing of the Trailguard ETU was carried out for six months in 1983 on six railroads under a variety of conditions and terrains. Trains averaged 1.6 km in length and ran from 8 to 90 km/h. Communications reliability for the 2 watt signal varied from 94 per cent to 30 per cent. Factors affecting the reliability were undulating tracks, mountainous terrain with many curves and tunnels, and foliage. UHF is absorbed by greenery. Other factors were the presence of steel such as a passing train on a parallel track or extensive wayside structures. These experiences with Trailguard are illustrative of the type of propagation problem frequently observed in UHF communications in the railway environment.[8.3]

(3) Equipment complexity. In addition to the basic control and monitoring hardware, the on-board equipment package must include a frequency-stable UHF transmitter, a receiver, and additional encoding circuits to provide the needed immunity to interference. Local intelligence may be needed in both the monitoring and braking systems to assure that data-rates can be accommodated in the UHF channel allocations. The units on each car will be relatively expensive. As a basis for comparison, the ETUs cost several thousand dollars each at present. Large-scale production would reduce the unit price.

(4) Antennas. It is unlikely that the ideal line-of-sight with the cab and optimum radiation characteristics will be achievable under the constraints that will be immposed by ruggedness and a secure, protected mounting arrangement.

(5) An on-board power supply is required.

End-of-train units are of particular interest here because they represent a device similar in many respects to the envisaged, on-board communications hardware. ETUs are limited to 2 watts of radiated power (in the U.S.A.) in the UHF bands, transmit digitized and security-encoded data, and employ antennas which, being mounted immediately above the last coupler, are far from ideally positioned. Thus, experience, such as that described in item (4) above, is pertinent to the assessment of on-board radio communications. In contrast, locotrol systems are able to radiate much higher power levels, have well-positioned antennas, and communicate over distances less than the length of the train.

Acceptable ETU performance is reported to be an 80 per cent average reliability.[8.3] To achieve this with a 2 watt UHF system, the head-end receiver must be capable of reliably decoding signals of one microvolt strength. Glenayre's experience with its Digitair ETU has been very good. A communications reliability of 98-100 per cent has been obtained in an extensive testing program. It may be necessary to have wayside repeaters in the more difficult terrain. Higher transmitter power levels could be considered, but there may be regulatory problems. Higher transmitter power at the car would not pose a serious power supply problem because the cars would transmit only about $(1/200)^{th}$ of the time, so that the 30 watt level used in locotrol systems, for example, represents an average power of 0.15 watts.

With regard to items (1) and (2), the problem of interference from adjacent or passing trains could be quite serious because data would be transmitted continuously in the proposed model. Each train would require an exclusive channel in its particular geographical location, and the transmitters and receivers on every car in the consist would have to be set to that channel as part of the train assembly procedure. Despite exclusive-channel operation, the receiving systems would have to have good adjacent channel rejection, that is high selectivity, because the transmitting antenna of a passing locomotive will be much closer to the cars than the antenna of the locomotive pulling them will be. The receivers will also have to have a high dynamic range, that is be able to work at the high levels which will exist at the head of the train as well as at the low levels occurring at the tail end and during fades.

Radio offers considerable flexibility in cab-to-car communications as well as the possibility of direct car-to-trackside communications. Radio systems patterned after the ETUs would be suitable for most surveillance functions. However, a higher degree of transmission reliability would have to be achieved through higher power and/or data encoding if brakes are to be controlled. Equally reliable communications in both directions between cab and car are necessary if "handshake" confirmations of the type used in locotrol are to be included in the brake-control strategy.

## 8.2 Inductive Coupling to Wayside Lines

Inductively coupled links have been used for many years on rapid-transit vehicles and on some European railways for train-to-wayside communications.[8.7,8.8,8.9,8.10,8.11,8.12] These systems operate in the frequency range 10 to 150 kHz and employ a two-wire transmission line running between the tracks as a transmission medium. Signals are transferred to and from the moving vehicle by means of a vehicle-mounted coil which couples to the electromagnetic fields of the transmission line The usage proposed here differs from the normal vehicle-wayside communications situation in that both the cab and the car would be coupled to the transmission line by inductive coupling coils. Signals launched from the cab would be coupled into the line, travel along the line past the cars of the train, and be sensed by the coils on each car. Transmission from car to cab would be accomplished in the same manner. Figure 8.2 illustrates the principle schematically. The advantages offered are:

(1) independent access to equipped cars

(2) the technology is well developed

(3) propagation characteristics are determined by the transmission line; wide variations along the route are avoided

(4) no coupling up operations needed.

There are, however, a number of quite significant problems.

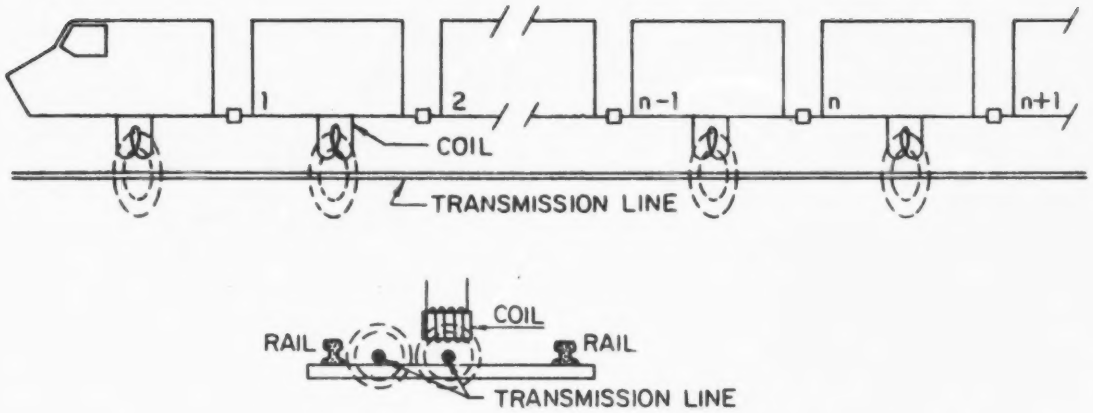



Figure 8.2 A schematic representation of cab-to-car communications through inductive coupling to a transmission line.

(1) A transmission line must be installed continuously along the route. This installation would have to be protected from weather and vandalism, and not interfere with roadbed maintenance. In principle, cables can be laid at shallow depths below the surface. While providing protection, this would greatly increase the difficulty of installation on existing tracks and would limit the degree of track-train coupling that could be achieved.

(2) Use of the system would be limited to those routes on which transmission lines had been installed. Thus, benefits would be derived only when both the train and wayside have been suitably outfitted.

(3) Because the signal path passes through two vehicle-to-line couplings, one at the locomotive and one at the car, the degree of coupling at each would have to be greater than is needed in the usual train-to-wayside communications link. Tight coupling requires very small separations between coil and line, of the order of a few centimetres. Such small separations would cause problems in winter as well as placing the coil assembly in a very vulnerable position.

(4) A break in the line would mean loss of communications between the part ahead and the part behind the break. Line continuity could be monitored by passing a current through the line between wayside stations.

(5) Bandwidth appears adequate for the quantity of digital data proposed. However, the coupling efficiency of the coil will vary dramatically with frequency. In one system examined, the transfer function, expressed in decibels, varies from -8 dB at 100 kHz to -28 dB at 10 kHz (20 dB/decade).[8.9] The data transmission strategy would have to take this characteristic into account.

(6) An onboard power source is needed.

The coupling coils in several systems examined were found to be from 6 to about 25 cm from the cable. Transmitter powers were in the 10 to about 50 watt range, while received signals are of the order of millivolts. The use of two coupling stages in series will require some or all of the following: tighter coupling, higher transmitter power, more sensitive receivers. Tighter coupling will make the coil-cable clearances impractically small, transmitter powers are already higher than those required in other transmission techniques and increases would make excessive demands on the on-board power source, and increased receiver sensitivity would most likely increase electromagnetic interference problems.

In the light of the problems identified, inductive coupling to a wayside transmission line does not appear to offer a practical solution to the in-train communications problems.

## 8.3 Radiating or Leaky Cables

During the 1970's, radiating or leaking transmission lines attracted attention as a radio transmission medium in environments where natural radio propagation was impractical or where it was desirable to restrict the transmission range.[8.10,8.11,8.12,8.13,8.14] Leaky-cable systems have been used in mines in Britain, France and Belguim to provide two-way radio communications within the mine tunnels.[8.15] The Montreal Metro uses a leaky cable communications system throughout its network to communicate with moving vehicles[8.16] and a leaky

coaxial cable system has been proposed for the Shinkansen lines in Japan. They have also been used to maintain two-way radio communications in long highway tunnels[8.17] and in railway tunnels.

Radiating cables take a variety of forms.[8.18] They may be a single conductor, a parallel pair, or coaxial cable with a loosely woven outer braid or with perforations in a solid outer conductor. Electromagnetic energy launched in a leaky line travels along it in two different modes, one essentially the same as the normal propagation, the other a radiating mode. Conversion from one mode to the other occurs at the slots or loose braid, or because of asymmetry with respect to the surroundings in the case of open field lines.

A radiating line can be treated as a continuous antenna radiating a controlled portion of the power it is carrying. Conversely, a signal transmitted near the line will be coupled into it and be carried along by the line. In the HF and VHF ranges, the coaxial versions shown in Figure 8.3 are preferred. Table 8.1 gives typical characteristics of some "leaky" coaxial cables currently available.[8.18,3.19,8.20]

The transmission scheme proposed here is similar in basic concept to the inductive coupling to a transmission line discussed in Section 8.2. However, they differ considerably in the frequency ranges in which they operate and the structure of the transmission lines employed. The idea is illustrated schematically in Figure 8.4.

In the leaky-line link, communications between cab and cars would be made by two-way radio through a leaky cable running either between the rails or alongside the track. Ideally, the leaky line would be completely passive, that is there would be no amplifiers (repeaters) in the line. Such a system would offer the following features:

(1) Independent access to equipped cars is possible.

(2) No coupling-up operations are needed.

(3) The technology has been successfully used in a number of applications which include mine and subway communications links, intrusion detection and restricted-range broadcasting. A variety of leaky coaxial cables are manufactured. Nevertheless, the technology is new and research into

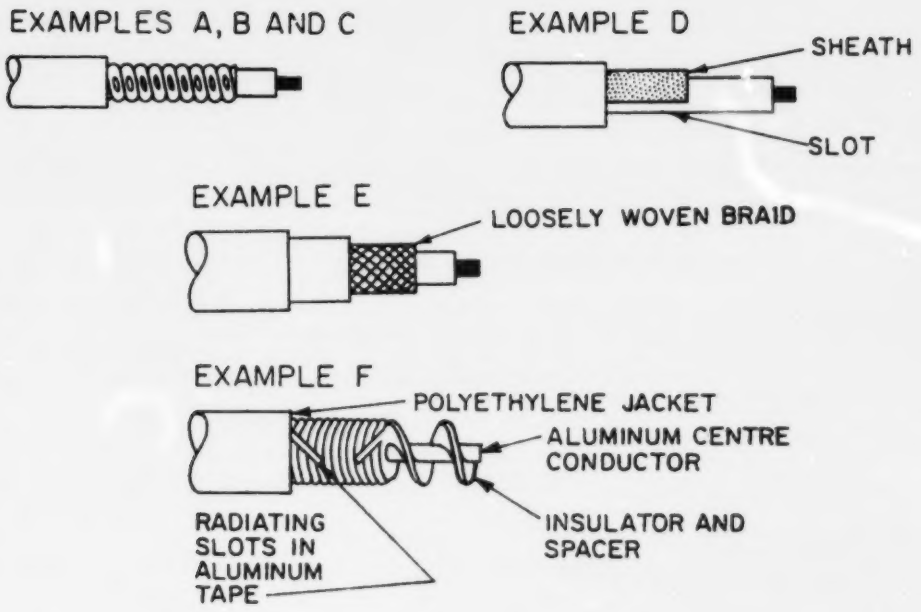



Figure 8.3 Four radiating coaxial cable structures. The letters A to F correspond to the characteristics decribed in Table 8.1. A, B and C have a perforated outer conductor, D has an incomplete shield which leaves a coninuous longitudinal slot, E has a loosely woven braid, and F has slots in an aluminim tape.

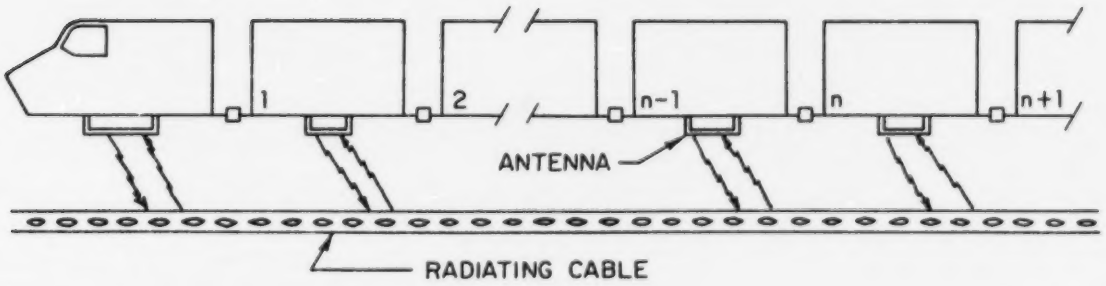



Figure 8.4 A schematic representation of cab-to-car communications through radio-frequency coupling to a radiating or leaky coaxial cable.

TABLE 8.1

RADIATING CABLE CHARACTERISTICS

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Impedance (ohms) | 50 | 50 | 50 | 60 | 75 | - |
| Outside diametre (mm) | 27.8 | 15.8 | 15.8 | 17.3 | 9.5 | 42 |
| VSWR 30-400 Mhz | 1.3 | 1.3 | 1.3 | - | - | - |
| Attenuation, free space* | | | | | | |
| 30 MHz, dB/km | 8 | 15 | 30 | 12 | 23 | |
| 150 MHz, dB/km | 15 | 36 | 62 | 26 | 50 | |
| 345 MHz, dB/km | 39 | 69 | 131 | 60 | 91 | |
| Attenuation, on ground† | | | | | | |
| 30 MHz, dB/km | 8 | 15 | 30 | 13 | 22 | |
| 150 MHz, dB/km | 23 | 36 | 131 | 31 | 45 | |
| 450 MHz, dB/km | 49 | 76 | 490 | 84 | 96 | 26 |
| Coupling loss (distance m) | | | | | | |
| 30 MHz, dB | 95(6) | 85(6) | 77(6) | 69(2)<br>79(10) | 82(2)<br>94(10) | |
| 150 MHz, dB | 70(6) | 75(6) | 57(6) | 82(2)<br>90(10) | 90(2)<br>104(10) | |
| 450 MHz, dB | 80(6) | 85(6) | 61(6) | 88(2)<br>94(10) | 97(2)<br>102(10) | 57(1.5) |

* D and E at 0.5 m above firm ground

† A, B, C and F mounted on concrete, D and E on firm ground.

propagation and coupling mechanisms is still being conducted. The electronic systems are essentially the same as for conventional two-way radios.

(4) Propagation along leaky cables is very stable and its characteristics are well defined. Variations of signal intensity due to terrain tunnels and wayside facilities would be eliminated. Propagation characteristics are not greatly affected by snow, ice or rain.

(5) The power levels needed for communications in these systems is usually less than a watt.

(6) Multiple channel operation and relatively large bandwidths are possible in the high HF and VHF ranges.

(7) In the usual mode of operation, antennas do not have to be in very close proximity to the radiating line to couple effectively to it. Therefore, antennas could be mounted in protected areas of the cars and above the level of the axles. This would overcome a major disadvantage of the inductive loop system (Section 8.2).

(8) Antennas designed to couple well into the cables without radiating strong fields would provide a degree of immunity to external interference as well as limiting interference to other services.

Attenuation and coupling loss are the parameters of the radiating cable which are of greatest consequence in assessing the performance of a communications link. An examination of the attenuation and coupling losses given in Table 8.1 reveals that the two are not really independent. Low coupling loss is accompanied by high longitudinal attenuation and vice versa. This is due to the fact that a cable producing a relatively strong external signal is radiating an appreciable fraction of the power propagating in the cable, and, therefore, the power level will decrease rapidly with longtudinal distance. System design requires a compromise choice between attenuation and coupling loss.

The coupling losses in Table 8.1 are defined as the ratio of the power received by an ideal isotropic receiving antenna, i.e. zero dB directional gain, to the power in the cable. Coupling loss can be partially offset by using an antenna with directional radiation characteristics. Directional gain increases with the size of the antenna measured in wavelengths. Thus, as wavelength decreases, the possible directional gain increases for an antenna structure of a given physical size. The most suitable antenna type would seem to be a slow-wave or surface wave structure in which a travelling wave is strongly radiated as it propagates. At a frequency of 150 MHz, a 6 dB gain should be achievable with a 2 m long, rod-like structure, while at 450 MHz a 2 m structure could provide at least 10 dB.

As in the case of the inductive coupling scheme, the coupling loss occurs twice in the signal path. This has important implications for

the path attenuation because coupling loss is generally of the order of 60 to 80 dB. Furthermore, the coupling mechanism in radiating-cable communications is a near-field phenomenon and does not obey the $1/r^2$ radiation density rule. The relatively small changes in coupling loss with distance can be seen in the data for cables D and E for which loss data at 2 and 10 m were available. It has been observed that coupling loss data does not necessarily continue to decrease as the antenna approaches the line.[8.13] In fact, at very close proximity coupling loss may pass through several oscillations with the minimum value remaining constant.

An example of an operating leaky-line communications system is the one in the Madrid subway.[8.21] The main characteristics are as follows:

Cable:

| | |
|---|---|
| Inner conductor: | 4.65 mm diameter |
| Outer conductor, corrugated and perforated tape: | 13.60 mm diameter |
| Outer sheath: | PVC |
| Charcteristic impedance: | 52.3 ohms |
| Coupling loss: | 77 dB |
| Attenuation: | 16 dB/km at 50 MHz<br>30 dB/km at 160 MHz<br>41 dB/km at 300 MHz |

Suspended 1 to 1.5 m from vehicle antenna

Train equipment:

| | |
|---|---|
| Transmitter: | 20 watts at 174 MHz |
| Receiver: | 0.5 V sensitivity with a 20 dB signal-to-noise ratio (50 ohms reference impedance) |
| Antenna: | 0 dB gain |

Link performance (theoretical):

| Distance (km) | Power in Cable (MW) | Signal on Receiver Aerial ($\mu$V) | Reception Probability (per cent) |
|---|---|---|---|
| 0.0 | 6.030 | 1,881 | 99.99 |
| 1.06 | 0.54 | 18 | 99.8 |
| 1.51 | 0.01 | 2.5 | 95 |
| 2.03 | 0.0001 | 0.25 | 34 |

Note that this communications link employs only coupling from vehicle to transmission line. The additional 77 dB coupling loss from the line to another vehicle would limit the range to impractically short distances. Improvement would be possible with lower attenuation, higher transmitter power (already 20 W) and tighter coupling by means of a directional antenna.

It is instructive at this point to estimate the path loss and power requirements for a cab-to-car link. A train length of 2 km will be assumed and cable D will be used at a frequency of 30 MHz. Coupling antennas would not have significant gain in the physical size that could be carried on a freight car. The receiver will require a signal of at least 130 dBW (decibels below a watt), to assure a 20 dB signal to noise ratio with a good low-noise receiver. Total path loss will be (69 + 2 x 13 + 69) = 164 dB. Therefore, the transmitter power will have to be 2,500 watts. The same calculation with cable F at 450 MHz gives a 166 dB path loss; however, at this frequency an antenna gain of at least 10 dB could be realized in a resonably sized structure, and the path loss becomes 146 dB. Transmitter power in this case would have to be 40 watts. Similar or worse results are obtained with the other cable types.

It is clear that the system as described falls short of viabilty, especially since no margin has been included in these calculations for the inevitable fluctuations that may occur due to standing waves, climatic conditions, etc. In the 450 MHz case described above, where the attenuation in the line was 26 dB but the coupling loss a relatively low 55 dB, the system could be dramatically improved, in fact by more than 26 dB in signal level if bi-directional amplifiers (repeaters) were placed every km along the leaky line. This, of course, would increase the cost of installation and maintenance, thereby destroying the positive features of the passive line.

Leaky lines operating in the lower HF region, that is 1 to 10 MHz, would have low attenuation and coupling factors less than 50 dB. While path loss might be sufficiently low, the possibilities for interference from other services would probably make this frequency range unsuitable for the highly reliable communications desired.

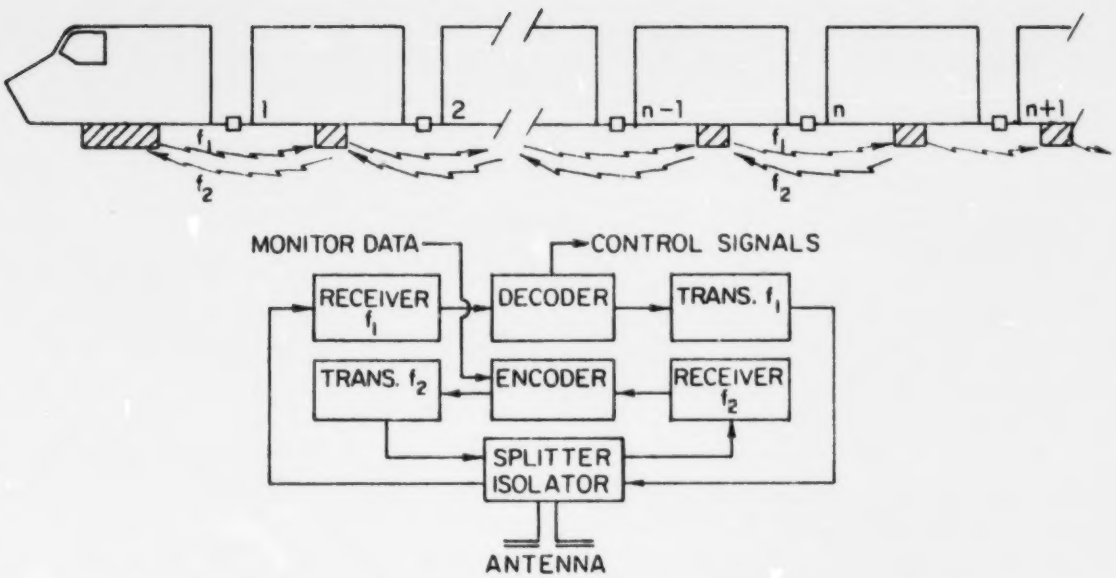



Figure 8.5 A schematic representation of on-board communications by means of a series of transponders. The essential components in the transponder are shown in the block diagram. TRANS = transmitter, $f_1$ and $f_2$ are the down-train and up-train channel frequencies.

At the car to which the request for data is addressed, two things happen: (1) the brake command is accepted and immediately retransmitted on the same channel to the next car down the train, and (2), a response containing the sensory information is composed, addressed to the previous transponder and emitted in the up-train channel. The relaying sequences continues in both directions so that the brake command travels to the end of the train in the down-train channel while the response from the addressed car makes its way to the head end in the up-train channel. Because transmissions in the two directions are at different frequencies, they can take place simultaneously without interference. However, only one down-train and one up-train transmitter would be on at any time. As with down-train signals, the up-train emissions would be ignored by transponders further down the train because of the signal addresses.

For each car in a 200-car train to be interrogated for sensory data every 10 seconds, the interrogation command must be transmitted 200 times in 10 seconds, or at a rate of 20 per second. If brake

The difficulties with the leaky line as an in-train communicaitons link are essentially the same as those listed in Section 8.2 for the inductively coupled line, except for item (5). Coupling loss is again a major factor because it occurs twice in the signal path. Only with the use of amplifiers in the line could a system be viable for long trains.

## 8.4 Transponder Link

The transponder link proposed here is based on an idea suggested by G. Izbinski, CP Rail, in which transponders on each car would relay messages along the train. A transponder is a receiver and transmitter, with associated electronic circuitry, which when it receives a signal automatically transmits a new signal. The transmission may be simply a repeat of the received data or transmission of a data stream composed in response to the received data. In the configuration described here, the transponder will have two complete transmitters and receivers operating on adjacent channels, but at sufficiently different frequencies that they do not interfere with each other. One channel would be for down-train communications toward the tail end, the other for up-train communications toward the head end. The same antenna would be used for both channels and by means of filters and isolators, both transmitters could operate simultaneously. Transmitters radiate a very low power level.

Figure 8.5 shows schematically how the system would work. The locomotive transmits a data block containing, for the sake of this discussion a brake command for all cars and the address of a car part way down the train with a request for sensory data. On receipt of the signal, transponder No. 1 checks the address fo see whether the message is for it and accepts the brake command. Since the message is not addressed to No. 1, it re-transmits the brake command, address and message in a signal which is picked up by transponder No. 2. The process is repeated until the addressed transponder is reached. The radio emissions from each transponder are radiated away from it in both the up- and down-train directions because a single low-directivity antenna would be used. Each re-transmission would be addressed to the next car in the consist, and would be ignored by the earlier cars through which the information had already passed.

commands are transmitted in the same data block, they will be received at each car every $1/20^{th}$ second, which is more frequently than the $1/10^{th}$ second proposed in the model. The transponder must relay the data blocks from one end of the train to the other in $1/40^{th}$ second if the interrogation and brake commands are to reach the end of the train and a response from the farthest car be received within the $1/20^{th}$ second interval. This requires the transponders to receive and retransmit in $(1/40)(1/200) = 0.125 \times 10^{-3}$. A cab-to-car data stream, as proposed, would contain a brake instruction of 24 bits, an interrogation code of 8 bits, and a relay address of 8 bits, for a total of 40 bits. A car-to-cab message would contain 112 bits of sensory data, an 8 bit source identification and a relay address of 8 bits, for a total of 128 bits. Since the transponder response time is limited to 0.125 msec., transmissions will have to take less than half of that time Therefore, for this calculation transmission will be limited to 0.05 msec. The largest bandwidth is needed for the car-to-cab communications in which 128 bits will be transmitted in 0.05 msec, that is a bandwidth of at least $2.56 \times 10^6$ Hz or 2.56 Mhz. In principle, such a bandwidth would not pose any technical problems at the UHF or microwave frequencies. Comments on data compression and coding in Section 6.2.5 also apply here.

Transponders would have transmitters sufficiently strong that they could communicate over several car lengths. This would permit unequipped cars to be included in the consist without interfering with the communications link. Furthermore, if a device failed it would be by-passed. This might require a response acknowlegement operation in the previous car so that if no acceptable response occurred the forwarding address would automatically be updated to that of the unit following the one which had failed. With regard to addressing, the data model of Section 6 suggested 8 bit addresses based on the numerical position of cars along the train, because the complete serial numbers, which would be available in the device memory, would be far too cumbersome for intra-train data movement. It is proposed that each car be given its numerical location in the train when the train is assembled. This could be accomplished by transmitting the appropriate position information to ech car as it moves past a wayside transmitter in the assembly yard. Or, each transponder could be in a "ready" position initially, accepting only the car's serial number as a pass-

word until its positional address has been assigned either by a central station or the cab.

It is known that 2 watts of radiated power in the UHF region is adequate for train-length communications by ETUs under ideal conditions. Therefore, one-tenth of this power should give coverage of up to 30 cars, since power density decreases as the square of distance. Thus, a power of 0.2 watts is suggested for the transponders. Another electromagnetic aspect of the system is propagation along the train, particularly if the transponder and its antenna are a single package mounted on the underside of the car. Whether the rails and car bottom will form a wave-guiding structure, loaded periodically by the wheels and axles, which aids or inhibits propagation, is not known and would have to be investigated.

The transponder system proposed here is only one possible configuration. More sophisticated coded concepts could probably eliminate the need for two channels. The idea needs further development, but appears to have potential and would very effectively exploit new digital signal processing technology.

Packaging and fabrication experience could be gained from the work on ETUs, BC Rail's LIC[8.21] interrogators and responder units and the various electronic automatic car identification systems proposed in recent years. It should also be noted that the transponder concept has been used by the military since World War II to produce identification signals by friendly aircraft in response to incident radar signals.

To summarize, the transponder link has the following features.

(1) It offers communications along the train without the need for a transmission medium in the wayside or the train.

(2) There are no inter-car connections to be made.

(3) Unequipped cars can be accommodated provided the transponders have a range of several car lengths.

(4) Low power levels may be used. It may be possible to operate the system within the limits allowed for unlicensed emissions.

(5) Because communications distances are short, propagation problems like those encountered in head-to-tail radio links should not be a problem.

(6) The electronic technology needed for implementation of the system exists and is well developed in other applicaitons. Development of circuits specific to this application would be necessary.

(7) The transponder system could be extended to car identification by wayside interrogators, and to other direct car-to-wayside communications.

(8) Special transponder units could be designed for quick attachment to foreign unequipped cars if necessary to complete a link. They would serve only as a stage in the link and would provide no sensory or control function.

The principal disadvantages seen in the transponder concept are:

(1) It is not suitable for voice links and the transmission of locotrol data in its usual format. (These functions can continue to be provided by two-way radio.)

(2) An on-board power source is needed.

(3) Additional security codes are needed to ensure that passing trains will not interfere with each other. Susceptibility to interference in general would have to be assessed.

## 9. ASSESSMENT AND CONCLUSIONS

The technical criteria under which the various schemes have been assessed are:

(1) Power Transmission. Can the system deliver power from the locomotive to the cars in sufficient quantity to operate electronic circuits and EP brakes?

(2) Data Rate. What data rates can be transmitted?

(3) Mode of Access. Is access serial or direct? In the serial mode the signal must pass from one car to another. In the direct mode the signal is

transmitted from the cab to the car, and vice versa, independently of equipment on other cars.

(4) Inter-Car Element. Does the system require a device to be connected between cars during coupling operations?

(5) Wayside Installation. Is wayside equipment necessary to facilitate communications along the train?

(6) Attenuation. The overall attenuation of the system for 200 cars. Attenuation is not an appropriate quantity for comparing all systems without also taking into account signal levels, amplification possibilities and interference levels.

(7) Hazards to Personnel. Are there inherent hazards to safety and/or health associated with the technique?

(8) Hardware complexity. Refers to hardware of the data link terminal on the car. Data processors, control circuitry and sensors are assumed to be the same in all systems.

(9) Hardware Failure. What are the consequences to the link of a failure in the equipment on an individual car?

(10) State of Development. This has been judged by noting whether the fundamental electrical and electronic elements are in regular use in other applications, are experimental or prototype systems, or are conceptual and need to be developed.

(11) Link Security. Immunity to Interference (EMI). Is the propagation medium stable, free from disturbance by environmental factors such as climate or changes in the surroundings? Can the system maintain an adequate signal-to-noise ratio in the presence of the likely sources of electromagnetic interference (EMI)?

(12) Suitability. This category deals with the system ruggedness, resistance to mechanical shock and vibration, and sensitivity to environmental factors such as dust, dirt, dampness and corrosive industrial atmospheres. To a large extent

ruggedness and environmental protection are a matter of packaging which, in turn, is often a matter of cost. It has been assumed that the electronic circuits could be adequately packaged and protected. There is certainly a great deal of experience with this aspect to be found in military equipment, missiles and the transportation fields in general. Large-scale integrated circuit implementations have proven to be able to reduce failure rates by orders of magnitude. Therefore, in considering suitability, attention has been directed toward other aspects that may pose problems in the freight train application.

(13) Cost Estimates. Cost estimates in Table 9.1 are intended to be indicative of the order of magnitude to be expected in implementing the systems and are not based on a detailed analysis. The estimates are based on the current cost of connectors, experience with the installation of the inductive connectors and transmission lines on the DAR gypsum train, the cost analyses in references 1.4 and 7.2, and the price ranges of ruggedized equipment such as the ETUs. These estimates refer only to link hardware.

An overview of the assessment is given in Table 9.1. Further explanations, interpretations and conclusions are given in the notes below.

## 9.1 Power and Data Requirements

A fundamental question underlying any consideration of new electronic technology on freight trains is whether on-board power sources are acceptable to the railways. While power sources were not part of this study, a number of schemes intended for railway use were encountered. These include piezoelectric and accelerometer generators operated by vibration, generators operated by the air-pressure system, solar cells, thermal energy from bearings, nuclear batteries and long-life lithium cells. In all cases instantaneous power is small and local storage would be needed. Thus, it seems rechargeable batteries of some sort are inevitable (generators driven from the axle have been ruled out for economic and maintenance reasons).

If batteries and other sources are not acceptable on freight cars, then the train transmission line appears to be the only practical way to

## TABLE 9.1

## FREIGHT TRAIN TRANSMISSION TECHNOLOGY: SUMMARY ASSESSMENT

| | 1<br>Power Transmission | 2<br>Data Rates (Mbps) | 3<br>Access Mode | 4<br>Inter-car | 5<br>Wayside Installation | 6<br>Attenuation 200 cars (dB) | 7<br>Hazards to Personnel |
|---|---|---|---|---|---|---|---|
| 1. Transmission Lines and Connectors: | | | | | | | |
| (a) Tandem | Yes | 0.1-0.5 | | 2 cables with connectors | | 5-15 | |
| (b) Single | Yes | 0.1-0.5 | Serial. Equipment needed on all cars | 1 cable with hermaphroditic connector | None | 5-15 | Possible shock hazard. Lines must be dead when connectors are disengaged |
| (c) Air-electric | Yes | 0.1-0.5 | | contacts on air-hose connector | | 5-15 (uncertain) | |
| (d) Tuned-inductive | No | 0.02-0.04 | | 1 cable with inductive connector | | 72 (24) | None |
| 2. Optical Fibres | no | 100-1000 | Serial. Equipment needed on all cars | Cable with EBL connector | None | 200 | Possibilty of accidental eye damage |
| Hybrid Optical/Electric | yes | | | Cable with EBL and electric contacts | | 200 | |
| 3. Waveguide | no | 1000 | Serial. Equipment needed on all cars | Choke flange & possible waveguide | None | 10-30 | Accidental MW emissions can cause burns, eye damage |
| 4. Radio | no | 1 (UHF) regulatory problems | Direct | None | None. May be needed in difficult terrain | 87 | None |
| 5. Inductive-Coupling to Wayside Line | no | 0.1 | Direct | None | Major. Continuous transmission line | High | None |
| 6. R.F. Coupling to Leaky Coaxial Line | no | 1 (UHF) | Direct | None | Major. Continuous leaky cable | 150 | None |
| 7. Transponder link | No | 1 (UHF) | Serial. Equipment <u>not</u> needed on all cars | None | None | - | None |

| 8<br>Hardware Complexity | 9<br>Hardware Failure | 10<br>State of Development | 11<br>Link Security and Immunity to EMI | 12<br>Suitability for Freight Railway Environment | 13<br>Link Cost per Car |
|---|---|---|---|---|---|
| Simple amplifier | Connector failure: link is disrupted<br><br>Electronics failure: transmission line is continuous and unaffected | Transmission lines are highly developed<br><br>Connector techniques exist. Adaptation needed.<br><br>Hermaphroditic coupling seal and contact cover need to be developed<br><br>Conceptual only. Needs to be developed.<br><br>Prototype exists. Has been field-tested. Improvement possible. | Stable propagation independent of surroundings.<br><br>EMI immunity very good if shielded. | Transmission line in conduit is suitable<br><br>Ruggedness and environment resistance have been demonstrated<br><br>Uncertain until prototype is developed<br><br>Uncertain until concept proven<br><br>Meets ruggedness and reliability requirements | (Includes $200 for transmission line installed)<br><br>$1,400<br><br>$ 800<br><br>$ 300 (uncertain)<br><br>$ 300 |
| Opto-electronic transmitters and receivers, coupling devices | Connector failure or electronics failure: link disrupted | Technology evolving. Experimental railroad applications. Has been effective in other harsh environments. | Stable, independent of surroundings. EMI immunity excellent | Ruggedness through appropriate packaging. Connector performance uncertain. Dirt will be a problem. | $1,500 (uncertain) |
| MW generator, MW receiver, waveguide couplers | Same as for transmission lines | Hardware well developed. Inter-car connector concept needs to be tested. | Must have environmental protection. EMI immunity very good. | Not suitable | $2,000-$4,000 |
| VHF transmitter, receiver, antenna | Failure of one unit does not disrupt communications with the others | Electronics technology well developed. Railroad examples in ETUs, two-way radios | Propagation problems. Occasional signal loss possible. Susceptible to interference. | Can be suitably packaged. | $2,000-$4,000 |
| LF transmitter, receiver, coupling coils | | Electronics highly developed. Used in rapid transit. | Noisy environment. Low signal levels due to high path attenuation. Probably poor. | Vulnerable coils. Vulnerable wayside installation. | $2,000-$4,000 plus wayside inallation $20,000/km. |
| VHF transmitter, receiver, special antenna | | Electronics well developed. Used in subways, mines. | Low signal levels due to high path attenduation. EMI immunity uncertain. | Antenna with adequate gain may be cumbersome. Vulnerable wayside installation. | $2,000-$4,000 plus wayside installation $20,000/km |
| VHF or MW transmitter, receiver, simple antenna and encoding electronics | No disruption if transmitter range is greater than one car length. | Electronics similar to ETU or some ACI systems. Needs to be developed. | Signal levels high because distances short. Expected to be secure with good EMI reistance. | Can be suitably packaged. Antenna is amenable to rugged packaging. | $2,000-$4,000 |

get power to the cars. The transmission of power from the locomotive to the cars would best be accomplished by two-wire transmission at low frequencies. Radio frequency and microwave power transmission have a number of potential problems and are an inherently inefficient means of power distribution.

Data rates for a fully instrumented and controlled train are really quite modest, and are most sensitive to the brake control mode. Common-mode and group-selective modes pose no problem to any of the systems examined, the data rate being comparable to those used between terminals and computers linked by telephone or similar lines. Only if every car in a 200-car train were to be given brake instruction update at a high rate, several times per second, would data rate become an important factor. Updating ten times per second requires 130 kbps.

If brake command up-dating rates can be reduced by a factor of 10 and some local intelligence introduced, even selective braking could be handled by a conventional voice channel.

## 9.2 Transmission Lines and Connectors

The transmission line with its simple hardware, simple interfacing requirements, ability to carry both signals and power and, when well shielded, its reasonably good immunity to interference, would seem to be a good candidate for an on-board communications link. Against it are the need to equip all cars and the loss of the system if the continuity of the line is broken. The principal technical uncertainty is the inter-car connector.

In Table 9.1, the use of transmission lines has been dealt with under four headings, each corresponding to a different aspect of connector technology.

> Tandem refers to the use of a receptacle and a connector on a flexible cable at each end of every car. This scheme appears to be practical and capable of meeting all requirements with currently available connector techniques. A modified version of the Pyle-National C-line would be one candidate for implementation. Engagement forces may be high for repeated

connection of a large number of connectors, but could probably be reduced.

Two connections must be made during each coupling operation. However, two parallel lines greatly reduce the probability of loss of communications because of a connector failure. More practical knowledge and field experience is needed in the railway environment before failure rates and expected reliability can be predicted.

(b) Single refers to a single cable terminated in a hermaphroditic connector at each end of the car. This would be the electical equivalent of the air-hose and connector. No electrical connectors have been found which satisfy the specifications set down in Section 7.1.2. However, connectors developed for other harsh environments have employed techniques which might be incorporated into a new connector designed specifically for the freight train inter-car application.

The two technical problems that must be overcome in order to realize an acceptable inter-car connector are (i) a hermaphroditic coupling mechanism with a good environmental seal, and (ii) a means of covering the contacts automatically when the connectors are disengaged.

There appears to be grounds for believing that a suitable connector could be developed. In the course of this study a number of innovative connector schemes have come to light. While many were not relevant to the freight train situation, they point out the tremendous innovative and inventive capability of the connector industry. The solution is not likely to be found in "new technology," but in the inventive application of existing technology and techniques.

It is not possible to say whether the single hermaphroditic connector would meet railway requirements until a design emerges and the concepts can be tested.

Because the mode of operation of the inter-car connector is not addressed in manufacturers' data and device evaluations, it would be valuable, in establishing whether the hermaphroditic concept is viable, to conduct tests on connectors which employ techniques of interest, even if all of the

features of the particular device are not suitable. Tests under simulated conditions and in the field should be conducted. A field test site exists already in the inductive connector installation in the DAR train in Nova Scotia. This could be exploited for field studies of other connector types as well.

(c) Air-electric refers to the addition of electric contacts to the face of a glad-hand air connector. A modification to the exterior surfaces of the glad-hand is envisaged, but not to the air passage. This system is purely conceptual at the moment. An important technical question is whether reliable contact can be assured after the contacts have been left exposed. However, the potential benefits, primarily the fact that there would be no additional coupling operation needed, are so great that this idea should be explored further.

(d) The tuned inductive connector is included for comparison. Its principal advantages are that it is inherently hermaphroditic, is coupled by the same kind of quick-connect/pull-apart mechanism as used in the air-hose connectors, and meets the ruggedness and environmental requirements of the freight train. It has received several years of field exposure on a unit train. Nevertheless, a train line employing the inductive connector would not be able to exploit fully the potential of transmission lines because it would not be able to deliver adequate power. The system bandwidth is just able to handle the proposed data rates.

However, it should be noted that the present embodiment of the connector, an inductive-coupling module in a modified glad-hand, is not the only embodiment possible. It has been shown that the attenuation can be reduced and the power-handling capability increases. The achievable attenuation is shown in brackets in Table 9.1. The maximum power-handling capacity envisaged in a hand-sized device would be suitable only for the recharging of on-board storage cells.

With regard to the transmission line itself, this study has assumed shielded, balanced, twisted-pair cable with the possibility of power

and signals being multiplexed on one line or transmitted on separate pairs within the same jacket. The attenuation values given in Table 9.1 are for communications. Attenuation decreases with decreasing frequency.

The handling of damp connectors with live power lines would be a serious safety consideration. A breaker system at the head-end would have to ensure that lines were dead before connectors are handled. Shock hazard is not a problem with the inductive connector.

## 9.3 Optical Fibres

A simple optical fibre link offers complete immunity from electrical interference, a propagation mechanism unaffected by its surroundings, and a bandwidth far in excess of the data needs proposed. But, because it needs both a power source on the car and an inter-car connector, the optical fibre alone is not a viable proposition. However, a hybrid optical-electrical connector has considerable potential. The connector problems are basically the same for the optical and electrical systems. Expandable-beam-lens techniques look like the best choice for an inter-car connector. A covering mechanism is certain to be needed to protect the optical interface from dirt and damage.

Continuity of the optical system throughout the length of the train is not possible without amplification. Thus, two failure possibilities exist which can disrupt the whole link: failure of a connector and failure of an opto-electronic repeater. Parallel and loop systems can provide redundancy.

Areas needing further investigation are the reliability and long-term stability of electro-optic systems and components, and the field servicing problems raised by the relatively high level of technology involved. Terminal hardware is still developing. In the future integrated-optics can be expected to provide reliable low-cost component systems suitable for environmentally secure packaging.

The results of experimental systems for passenger transportation systems in Japan and Germany should be followed closely.

## 9.4 Waveguide

Waveguides are relatively bulky, expensive, require substantial environmental protection, and are not a practical way to send quantities of power along a train. Microwave signal sources tend to be relatively expensive. An inter-car connector appears to be feasible, but would have to be developed. On the whole, waveguide does not appear to offer an advantage over lower-frequency transmission lines.

## 9.5 Radio, Inductive Coupling and Leaky Coaxial Cable

Radio, inductive coupling to a transmission line, and radio-frequency coupling to a leaky coaxial line all offer communications between cab and car without inter-car connections, without requiring every car to be equipped, and without loss of the whole system if one on-board unit fails. All need on-board power sources.

The radio frequency systems require VHF or microwave transmitters, receivers and antennas. As a general rule, component costs increase with frequency.

With radio a serious problem is the stability of propagation along the train. Also, the open nature of the medium makes it susceptible to interference. Coding can ensure high immunity to interferences but cannot compensate for the occasional absence of signals. Radio systems patterned after the ETUs would be suitable for most surveillance functions. However, a higher degree of transmission reliability would have to be achieved through higher power and/or data encoding if brakes are to be controlled. Equally reliable communications in both directions between cab and car are necessary if "handshake" confirmations of the type used in locotrol are to be included in the brake-control strategy.

Both the inductively coupled system and the leaky coaxial cable system require two stages of coupling in series. It is now clear that the attenuation of the signal path plus the attenuation of the line will reduce the signals to undesirably low levels or require excessively high transmitter powers. The inductive-coupling coils will have to be very close to the transmission line and this will make them vulnerable to damage and a problem in winter.

In both cases the wayside instaliation would have to be protected against vandalism, damage during roadbed maintenance, and climatic factors, making it an expensive proposition. Broken transmission lines would have serious consequences for the control signals. Neither of these propositions is considered to be viable for Canadian freight trains.

## 9.6 Transponder Link

The relaying of signals along the train by means of transponders on each car is the most interesting concept using radio propagation which has been encountered. It requires no inter-car connection and no wayside installation. Because the necessary transmission range is normally one car length, signal levels would be high with low transmitted power and the system is not likely to be greatly affected by propagation anomalies. If the transmitter is designed to have a range of several cars, then every car in the consist does not need to be outfitted. Furthermore, failure of one unit would not disable the system. The transmitter needs to radiate only a low power, the receiver does not need high sensitivity, and it should be possible to use a simple antenna, amenable to rugged packaging and installation in a protected location. The propagation of electromagnetic waves in the "guide" created by cars and rails should be studied. Communications between cars and trackside stations is possible.

The transponder link is the most interesting concept based on radio propagation and warrants further investigation and development, provided an on-board power source is accepted.

## 9.7 Summary of Conclusions

The main conclusions to be drawn from the study are:

(1) The only practical way of distributing power from the locomotive to the cars is by two-wire transmission line.

(2) A train-length transmission line is a very attractive communications link because of its simplicity and ability to carry both signals and power.

(3) Tandem cabling with receptacle and plug at both ends of the cars looks practical with modifications to existing connectors. Engagement forces should be reduced. The Pyle-National C-line is a good candidate. Laboratory and field-test information specific to the inter-car application is needed before reliability can be estimated with confidence.

(4) No truly hermaphroditic connectors have been found which meet the requirements of the inter-car connector. However, connectors developed for other applications have employed techniques which could prove valuable in a new inter-car connector design. Prospects for successfully developing an acceptable connector appear to be good. The most promising techniques need to be assessed experimentally in a real or simulated railway environment before firmer conclusions regarding the viability of an eventual connector can be drawn.

(5) An air-electric connector employing contacts in the glad-hand air-hose connector would have much to offer. There is some question as to whether a contact mechanisum can be successfully implemented.

(6) The tuned, inductive connector, despite its limitations, remains the simplest, least-expensive, inter-car connector meeting the reliability and ruggedness requirements of the railway environment.

(7) Optical fibres are of interest only if combined with an electric power line. Inter-car connector requirements are essentially the same as for electric connectors. The main advantage of optical fibres in the freight train application is their complete immunity to electromagnetic interference. Highly reliable opto-electronic repeaters are needed on board cars. This evolving technology shows great promise, but more needs to be known about reliability, long-term stability and maintenance.

(8) Waveguides are not considered to offer any advantages not available in other systems.

(9) Radio offers cab-to-car communications without inter-car connections and without loss of the whole system if one link fails. The primary

technical problem is transmission reliability in the environment of the moving train. With adequate power and EMI protection through coding, direct two-way radio could provide a viable communications link. Channel allocation, regulatory aspects and data-transmission protocols are areas needing further study. An on-board power source would be needed.

(10) Inductive coupling to a transmission line and radio frequency coupling to a leaky coaxial cable are not considered suitable for freight train applications because of the very high transmission path losses and the need for a continuous wayside transmission line.

(11) The transponder link is the most interesting concept employing a propagation medium external to the train. Inter-car connections and a wayside installation are not required. Failure of a unit or unequipped cars in the consist do not disrupt the link if the transponders have a range of several car lengths. This concept warrants further exploration provided an on-board power supply is acceptable.

## 10. RECOMMENDATIONS

The recommendations given below can be grouped according to the source of electric power envisaged on the cars. If power sources on every car are not acceptable, as has been suggested by people in the railway industry, then items (1), (2) and (3) are pertinent. However, if the railways are willing to also consider independent, on-board sources, then items (4) and (5) are of interest and, if implemented, would open the door to some quite attractive train communications concepts.

(1) An experimental assessment program should be undertaken to establish how well the most promising connector techniques would perform in the freight train environment. Candidate connectors for the tandem model as well as the techniques of interest to a new hermaphroditic connector should be included. Tests in real field environments as well as laboratory simulation would be valuable. A field test site already exists in the transmission line installed on the DAR captive fleet in Nova Scotia. It should be exploited for the studies of other

types of connectors as well as the inductive connector currently in place.

(2) Connector manufacturers expressing an interest in the inter-car connector as a possible product line are, in alphabetical order, AMP, ITT Cannon and Pyle-National. However, they have some reservations as to whether the railways are genuinely interested in the train-line concept. Connector manufacturers should be invited to prepare prototypes for evaluation with funding, at least in part, by Transport Canada and the railways as an incentive. This recommendation does not preclude the more financially modest assessment proposed in recommendation (1) above, which would be the precursor to prototype development.

(3) The experimental programs evaluating optical-fibre links on passenger vehicles in Japan and West Germany should be monitored closely. Because coupling and protection are essentially the same for electrical and optical contacts, the studies recommended in item (1) are pertinent to the hybrid electrical-optical connector. Further information should be sought regarding the reliability of the expanded-beam-lens technique and electro-optic terminals and repeaters.

(4) The transponder link and the direct cab-to-car radio link require on-board power. Since both of these systems eliminate the constraints of (i) an inter-car coupling-up operation, and (ii) vulnerability of the system to failure of one component, they could prove more attractive than transmission-line systems if suitable power sources were available on the cars. Therefore, a study of energy storage devices and methods of replenishing them should be undertaken immediately.

(5) The transponder link should definitely be given further consideration if an on-board power source can be accepted. The design and development of an experimental system should be undertaken in order to address concrete problems of data encoding needs and protocols, communicatons modes, optimum frequency, transmitter power-levels, receiver sensitivity, and packaging. An investigation of the "waveguiding structure" formed by the car body, wheels and axle, and the

rails would be part of this development. Evaluation should include a relative assessment of the transponder link and direct radio links performing the same monitoring and control functions.

## REFERENCES


1.1 R.L. Smith and J.L. Frarey, "On-board Failure Protection Requirements for Railroad-Vehicle Equipment," U.S. Dept of Transportation, Federal Railraod Administration,, Report No. FRA/ORD-78-72, Mach 1979.

1.2 J B. Hopkins and R.M. Snow, "On-Board Component Failure Detecion Systems for Freight Cars: Concepts, Technology and Benefits," Proc. of the 1982 Joint ASME/IEEE Railroad Conference, Erie, PA, April 19-22, 1982, pp. 43-52.

1.3 "Electro-pneumatic Train Brakes - State of the Art Review and Development Program for Freight Train Applications," prepared by Maughan Railway Consulting for Transport Canada Research and Development Centre, Report No. TP 1435, 1977.

1.4 E.K. Bender, L.E. Wittig and H.A. Wright, "Evaluation of the Costs and Benefits of Advanced Braking and Coupling Systems," Dept of Transportation, Federal Railroad Administration, Report No. FRA/ORD-80/49, October 1980.

1.5 E.K. Bender, L.E. Wittig and H.A. Wright, "Recommendations for Research and Development of Advanced Railroad Braking and Coupling Systems," U.S. Dept of Transportation, Federal Railroad Administration, Report No. FRA/ORD-81/24, March 1981.

1.6 J.L. Brooks, "Heat-Activated Alarm System for Railroad Boxcars Carrying Explosives," Civil Engineering Lab (Navy), Port Hueneme, CA, CEL-TN-1512, December 1977.

1.7 G.E. Allen et al., "Prevention of Roller-Bearing-Initiated Burnoffs in Railroad Freight Car Journals," U.S. Dept of Transportation, Federal Railroad Administration, Report No. FRA 79-5, January 1979.

1.8 B.B. Saunders et al , "Monitoring Devices for Railroad Safety," U.S. Dept of Transportation, Federal Railroad Administration, Report No. FRA/ORD-82-46.1, August 1982.

1.9 P. Nance, "G-Sensing Derailment Detector," U.S. Dept of Transportation, Federal Railroad Administration, Report No. FRA/ORD-80/75, October 1980.

1.10 G.J.M. Aitken, "A Communications System for Long Trains," Canadian Institute of Guided Ground Transport, Queen's University, Kingston, Ontario, Canada, Report No. 75-4, February 1975.

1.11 G.J.M. Aitken, "Inductive Coupling for Transmission of Braking Signals in Long Freight Trains," Canadian Institute of Guided Ground Transport, Queen's University, Kingston, Ontario, Canada, Report No. 77-4, January 1977.

1.12 G.J.M. Aitken, "Inductively Coupled Connectors for Signalling and Brake Control on Long Freight Trains," Canadian Institute of Guided Ground Transport, Queen's University, Kingston, Ontario, Canada, Report No. 78-17, December 1978.

1.11 G.J.M. Aitken, "Field Testing of Inductive Connectors," Canadian Institute of Guided Ground Transport, Queen's University, Kingston, Ontario, Canada, Report No. 81-15, March 1982.

6.1 "Some Aspects of the Transmission of Safety Information," ORE Report No. DT-86(A118)E, UIC, Utrecht, November 1978.

6.2 E.E. Gelbstein, "Assessment of Recent Technological Progress Relevant to the Transmission of Safety Information," ORE Report No. DT-95(S1019)E, UIC, Utrecht, October 1979.

6.3 H.W. Keinath and N.O. Kinderman, "Data Radio Systems for Railway Communications and Control," Railways in the Electronic Age, IEE Conference Publication No. 203, 1981, pp. 136-145.

6.4 R.A. Ripper, "On Train Communications - Current and Future Trends," Railways in the Electronic Age, IEE Conference Publication No. 203, 1981, pp. 152-156.

6.5 R.C. Short, "The Impact of Microelectronics on Railway Signalling," Railways in the Electronic Age, IEE Conference Publication No. 203, 1981, pp. 6-10.

6.6 D.A. Tugal and O. Tugal, Data Transmission: Analysis, Design, Applications (McGraw-Hill, New York, 1982).

6.7 P. Bylanski and D.G.W. Ingram, Digital Transmission Systems (Peregrinus, Stevenage, Herts., 1976).

6.8 K. Dreimann, "Electronic Equipment on Rail Vehicles," ZEV-Glas. Ann., Vol. 108, January 1984, pp. 21-26 (in German).

6.9 G.A. Smith, "Principles of Brake Control System Design," Institution of Mechanical Engineers Conference Publication C156/79, 1979, pp. 37-46.

6.10 P. Lohmeier and G. Kessel, "New Developments in the Field of Electropneumatic Brake Control Systems," Glassers Annalen ZEV, Vol. 103, February 1979, pp. 125-135 (in German).

6.11 "Specifications for the Experimental System for Transmitting Information Through the Train Line," ORE Report No. A103/RP 4/E, UIC, Utrecht, October 1977.

7.1 Transmission of Information Through the Automatic Coupler," ORE Report No. A103/RP 1/E, UIC, Utrecht, 1966.

7.2 R.K. Mathewson, R.A.C. DiMichele and F.E. King, "Railway On-Board Hot-Box Detector Evaluation," prepared by Dynamic Sciences Limited, Montreal, for the Transportation Development Centre, Transport Canada, Report No. TP-4055E, 1982.

7.3 B.B. Saunders et al., "Monitoring Devices for Railroad Safety," prepared by National Space Technology Lab for the FRA, Report No. DOT/FRA/ORD-82/46.1, 1982.

7.4 S.K. Punwani, L. Eshelman and A.T. Kearney, "Advanced Coupling Concepts Project - Phase 1½ report including general econmic model," AAR Technical Centre, Report No. R-285, 1977.

7.5 G.F. Guth, "Updated and Quantificaton of Failure Rate and Mathematical Models for Connector as Specified in MIL-HDBK-217B," 10th Annual Connector Symposium Proceedings, Cherry Hill, N.J., October 19029, 1977, pp. 69-76. Also 1982 coefficient data, MIL-HDBK-217D.

7.6 F. Sevcik, "Lessons Learned from Failure of Connectors," 15th Annual Connector and Interconnector Technology Symposium Proceedings, Philadelphia, PA, November 1-2, 1982, pp. 387-392.

7.7 H. Hoft, "An Analysis of Electrical Contact Failures in Practical Operation," Nachrichtentech. Elektron., Vol. 29, No. 4, 1979, pp. 151-153 (in German).

7.8 P. Stuhlmuller, "Connector Problems," Elektronik (Germany), Vol. 27, July 1978, pp. 46-51 (in German).

7.9 M. Antler, "Sliding Wear of Metallic Contacts," IEEE Trans. on Component, Hybrids, Manufacturing Technology, Vol. CHMT-4, pp. 15-29, March 1981.

7.10 "Trans-Power Head-End Power Connectors," Pyle-National Company, 1334 N. Koster Avenue, Chicago, IL., Bulletin No. TR-100, 1982.

7.11 "Trainline Plugs and Receptables," Pyle-National Company, 1334 N. Koster Avenue, Chicago, IL., Bulletin No. 1252-G.

7.12 "Series C-158 Connectors Meeting UIC International Railway Standards," Amphenol-Tuckel Electronics GMBH, Munich, West Germany, Bulletins CC/SC 158-4/75/AG and CC10/SC 15801/4/83 B.

7.13 J. Janatka, "Ship-to-Shore C-Line," Proc. of the 13th Connector Symposium, Philadelphia, PA, October 8-9, 1980, pp. 379-386.

7.14 "Powerpole Connectors," Anderson Power Products, 145 Newton Street, Boston, MA., Brochure No. 156086, 1984.

7.15 "Ampower Terminals," AMP Incorporated, Harrisburg, PA., Catalog 73-219, 1981.

7.16 J.B. Minter, "New High Reliability Missle Interconnect Bus System," 11th Annual Connector Symposium Proc., Cherry Hill, N.J , October 25026, 1978, pp. 275-282.

7.17 J.H. Whitley, "The Anatomy of a Contact: A Complex System," Insulation/Circuits, Vol. 27, Part I, October 1981, pp. 97-98, Part II, November 1981, pp. 60-64 and Part III, December 1981, pp. 83-86.

7.18 G.L. Ginsberg, "Connectors," Electronic Packaging and Production, July 1982, pp. 233-249.

7.19 G. Kovacs, "Failure Analysis of Contaminated Gold-Plated Connector Contacts from Operating Communications Equipment," IEEE Trans. Component, Hybrids, Manufacturing Technology, Vol. CHMT-5, March 1982, pp. 95-101.

7.20 M. Antler, "Field Studies of Contact Materials: Contact Resistance Behaviour of Some Base and Noble Metals," IEEE Trans. Components, Hybrids Manufacturing Technology, Vol. CHMT-5, September 1982, pp. 301-307.

7.21 S.W. Updegraff, "Better Than Gold: A Palladium-Nickel Coating System for High Reliability Connectors," Proc. of the 33rd Electronics Components Conference (IEEE), 1983.

7.22 J.H. Whitley, I-Y Wei, and S.J. Krumbein, "A Cost-Effecitve, High-Performance Alternative to Conventional Gold Plating on Connector Contacts," IEEE Trans. Components, Hybrids, Manufacturing Technology, Vol. CHMT-6, December 1983, pp. 395-407.

7.23 C. Waddilove, "Maritime Connectors for the Future," New Electronics (Great Britain), Vol. 10, 25 January 1977, pp. 96-97.

7.24 "V.E. Transportation Series Connectors," ITT Cannon, Santa Anna, CA, Bulletin VE-2, 1979.

7.25 "Cannon Connectors for Hostile Environments of Energy and Commercial Industries," ITT Cannon, Fountain Valley, CA, Catalog No. HEC-3, June 1983.

7.26 "Transmission of Informaiton Through the Train Line," ORE Report No. A103/RP 3/E, UIC, Utrecht, 1976.

7.27 M.J. Coleman, "A New Filtered Connector Design to Combat Today's High Radiated Field Strength Intensities," 12th Annual Connector Symposium, Cherry Hill, N.J., October 17-18, 1979, pp. 397-408.

7.28 P. Dobrogowski and J. Schroeder III, "EMI Control Techniques Using Filtered Connectors," 12th Annual Connector Symposium, Cherry Hill, N.J , October 17-18, 1979, pp. 237-238.

7.29 W.B. Fagerstrom and E.T. Nicotera, "Fretting Corrosion in Connectors," 14th Annual Connectors and Interconnectors Symposium Proceedings, Philadelphia, PA, November 11-12, 1981, pp. 303-312.

7.30 "Potential of Fibre Optics for Transportation Applications," a report prepared by IBI Group for Transport Canada, No. TP-1804, November 1978.

7.31 E A. Lacy, Fiber Optics (Prentice-Hall, Englewood Cliffs, N.J., 1982).

7.32 Helmut F. Wolf, editor, Handbook of Fiber Optics: Theory and Application (Garland, New York, 1979).

7.33 E.W. Riley, "Transmission Characteristics of Optical Fiber Waveguides," AAR Communications and Signal Section 23rd Annual Meeting, Toronto, October 17-19, 1983.

7.34 M.J. Howes and D.V. Morgan, Optical Fibre Communications (John Wiley, Chichester, 1980).

7.35 C.P. Sandback, editor, Optical Communications Systems (John Wiley, Chichester, 1980).

7.36 J. Armstrong, "Fiber Optics Moves Onto the Main Line," Railway Age, August 1983, pp. 46-49.

7.37 "Future Looks Bright for Optical Fibres," International Railway Journal, July 1982, pp. 57-60.

7.38 J.A. Early, "Fiber Optic Communication System," AAR Communication and Signal Section 23rd Annual Meeting, October 17-19, 1983, Toronto.

7.39 E.E. Gelbstein, "Optical Communications Based on Optical Fibres and Their Use in Railways," ORE, Utrecht, Report No. DT 100 (S 1017), April 1980.

7.40 P.A. DeParis, "Systèmes optoelectroniques à la SNCF," Revue Generale des Chemin de Fer, January 1984, pp. 1-10.

7.41 D.M. Knecht, W.J. Carlsen and P. Melman, "Expanded Beam Fiber Optic Connectors," GTE Products Corporation Technical Bulletin.

7.42 G.F. Dorsey, "Fiber Optic Rotary Joints -- A Review," IEEE Trans. on Components, Hybrids, Manufacturing Technology, Vol. CHMT-5, No. 1, March 1982, pp. 37-41.

7.43 J.F. Ryley et al., "A Military Duplex Lensed Connector for Rapid Field Assembly," 15th Annual Connector and Interconnector Technology Symposium Proc., 1982, Philadelphia, pp. 28-34.

7.44 G.Eberle et al., "Lichtleitertechnik auf elektrischen Bahnen," Elektrische Bahnem, Vol. 79, No. 4, 1981, pp. 140-144.

7.45 K. Saito et al , "On-Board Optical Data Communications Network for Train Control," Hitachi Research Laboratory, Katsuta-shi, Japan 312, 1982. Also, "Optoelectronic Control Systems for Magnetically Suspended Trains," Technocrats, Vol. 15, No. 10, October 1982, pp. 18-20.

7.46 T. Tanino and S. Fuzita, "Applications of Optical Fibres to Trains," JREA, Vol. 24, 1981, pp. 13,891-5 (in Japanese).

7.47 R.C. Schwickert, K.V. Monaghan and E.F. Fenili, "A New, Environmentally Sealed, Hybrid Fiber Optic/Electrical Multi-Pin Connector " 11th Annual Connector Symposium Proc., October 25-26, 1978, Cherry Hill, N.J., pp. 208-218.

7.48 G.L. Ragan, Microwave Transmission Circuits (McGraw-Hill, New York, 1948), pp. 193-294.

8.1 "Locotrol Model 1055S Locomotive Remote Control System," Technical Report by Radiation Incorporated, Control Division.

8.2 "2nd Generation for FEC's Red Box," Progressive Railroading, Vol. 23, March 1980, p. 87

8.3 "Digital GL 6620," Glenayre Advertising Bulletin No. GL176-0054, 1983.

8.4 "End-of-Train Monitor," Progressive Railroading, November 1983, pp. 57-58.

8.5 "Train Guard," Union Switch and Signal Advertising Bulletin No. 392, 10/83.

8.6 R.L. Robinson, "A Radio-Operated Device for Locating Defective Brake Valves Which Cause Undesired Emergency Brake Applications in Freight Trins," Proceedings of the 17th AAR Communicaitons and Signal Section Meeting, Minneapolis, 26-28 September 1977, pp. 41-48.

8.7 P S. Kalra, "A Green Light for Advanced Train Controls," IEEE Spectrum, February 1979, pp. 44-49.

8.8 D.M. Petrie and R.C. Milnor, "Advancements in Automatic Train Control for Rapid Transit Systems," Conference Record, 13th IAS Annual Meeting, Toronto, October 1-5, 1978.

8.9 T.N. Johnstone, "Development of an Inductive Communications System for Morgantown People Mover," 29th IEEE Vehicle Technology Conference, Arlington Heights, Ill., March 27-30, 1979.

8.10 A.D. McAulay, "Progress in Signalling for Track Guided Systems," ASCE Journal of Transportation Eng., Proc., Vol. 101, No. TE4, November 1975, pp. 621-638.

8.11 G.W. Hutchings and D.J. Cree, "Longitudinal Track to Vehicle Communications," British Railway Board (Institution of Electrical Engineering), Report No. 117, 1974, pp. 153-161.

8.12 G. Besacier, "Les systèmes de transmission entre la voie et les trains due Metro de Paris," Automatisme, Vol. 18, No. 10, October 1973, pp. 333-340.

8.13 J.C. Beal et al., "Continuous-Access Guided Communication (CAGC) for Ground Transportation Systems," Proc. IEEE, Vol. 61, No. 5, May 1973, pp. 562-568.

8.14 Q.V. Davis, "Restricted Range Communications Systems," Proc., Conference on Electromagnetic Compatibility, Univ. of Southampton, England, September 16-18, 1980 (Inst. of Electronics and Radio Engineers, Issue No. 47, pp. 41-46, 1980).

8.15 P. Delongne, "Radio Goes Underground," IEEE Spectrum, July 1980, pp. 26-29.

8.16 E.R. Leech and W.T. Outlaw, "A Communications Systems Custom Designed for the Montreal Metro Rapid Transit Subway," Proc. of the 17th AAR Communications and Signals Section Meeting, Minneapolis, 26-28 September 1977, pp. 6-21.

8.17 T. Kishimoto, "Train Radio Communications System Usng Leaky Coaxial Cable," Japanese Railway Engineering, Vol. 18, No. 3, 1978, pp. 13-14.

8.18 D.J. Cree and L.J. Giles, "Practical Performance of Radiating Cables," The Radio and Electronics Engineer, Vol. 45, No. 5, May 1975, pp. 215-223.

8.19 S. Okada et al., "Leaky Coaxial Cable for Communication in High Speed Railway Transportation," The Radio and Electronics Engineer, Vol. 45, No. 5, May 1975, pp. 224-228.

8.20 Andrew Corporation, 10500 W. 153rd Street, Orland Park, IL, U.S A , Catalog No. 32, 1983, pp. 144-145.

8.21 L. Berzosa, J.M. Ramos and J. Monteys, "Radiocommunications in 'Metro de Madrid'," Railways in the Electronic Age, IEE Conference Publication No. 203, 1981, pp. 146-151.

8.22 "Digitrac System GL 6000," Glenayre advertising bulletin No. 6000-8-80 BL1/2 B02.

Literature not referenced in the text:

C. Bach et al., "Study of Advanced Technology on Japanese National Railways," prepared by Railway Association of Canada for Transportation Development Centre, Transport Canada Report No. TP 4543E, 1983.

Transport Canada
Development

Transports Canada
Développement

TP 5703E

# Review of Signal and Power Transmission Technology for Freight Trains

*Summary Report*

Prepared for
Transportation
Development Centre

Transport Canada

JULY 1984

Canada

CA1
DIC 847
84
R27S
c.2

CIGGT Project No. PRO-136

CIGGT Report No. 84-4
Transport Canada Report No. TP-5703E

# REVIEW OF SIGNAL AND POWER TRANSMISSION TECHNOLOGY FOR FREIGHT TRAINS

Summary Report

prepared by

G.J.M. Aitken
Department of Electrical Engineering
Queen's University at Kingston

for

Transportation Development Centre, Transport Canada,
under contract No. OSD83-00070

Canadian Institute of Guided Ground Transport
Queen's University at Kingston, Ontario
K7L 3N6

July 1984

## ACKNOWLEDGEMENTS

The author wishes to thank the many individuals, companies and agencies who provided information and advice on the topics of this study. Of special note were the contributions of S. Riddell, Pyle-National; T. Thornton, AMP Corp.; and R.J. Pomeroy, Glenayre Electronics. Valuable assistance was received from I. Henry and J. Taylor, Toronto Transit Commission; J.B. Hopkins, U.S. Department of Transportation; C. Wright, WABCO; Ms Donnolly, CN Library; Sheila Johnson, Douglas Library, Queen's University; and the personnel of UTDC. The author is grateful for the excellent support provided by Jane Law and Janice Bélanger, CIGGT Librarians, for whom no document or report was too obscure or too remote to obtain. Special thanks to Sherrill Arnold for her participation in the preparation of this report.

This report resulted from research conducted through the Canadian Institute of Guided Ground Transport. The report represents the views of the author and does not necessarily have the endorsement of the University or the other participating organizations.

Ce rapport est également disponible en français: TP5703F.

## REPORT DOCUMENTATION FORM

| 1. Transport Canada Report No. | 2. TDC Project No | 3. Recipient's Catalogue No. |
|---|---|---|
| TP5703E | 6053 | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| REVIEW OF SIGNAL AND POWER TRANSMISSION TECHNOLOGY FOR FREIGHT TRAINS<br>Summary Report | July 1984 |
| | 6. Performing Organization Report No.<br>84-4 |
| 7. Author(s)<br>G.J.M. Aitken | 8. Transport Canada File No.<br>D1465-158-6 |
| 9. Performing Organization Name and Address<br>Canadian Institute of Guided Ground Transport (CIGGT)<br>c/o Queen's University<br>Kingston, Ontario K7L 3N6 | 10. DSS File No.<br>11SD.T8200-3-3527 |
| | 11. DSS or Transport Canada Contract No.<br>OSD83-00070 |
| 12. Sponsoring Agency Name and Address<br>Transportation Development Centre, Suite 2421<br>1000 Sherbrooke St.W., Montreal, Quebec H3A 2R3<br>Canadian Pacific Ltd, Windsor Station<br>Montreal, Quebec H3C 3E4 | 13. Type of Report and Period Covered<br>Summary, Aug/83-July/84 |
| | 14. Sponsoring Agency Code<br>TDC 6053; CP 1871-Q-19 |
| 15. Supplementary Notes<br>Summary of TP5704E/CIGGT 84-4, "Review of Signal and Power Transmission Technology for Freight Trains, July 1984 | 16. TDC Project Officer<br>M. Avni |

17. Abstract

A data model and the power requirements for freight train monitoring and brake control are established as a framework for technology assessment. Transmission systems employing on-board and external transmission media are examined. Conventional two-conductor transmission lines have much to offer in simplicity, ruggedness and reliability. Consequently, their weak point, the inter-car connector, has been examined in some detail. No connectors were found which fully met a set of requirements defining the ideal connector; however, a number of potentially useful connector techniques were identified in other applications and warrant further consideration. Fibre optics have promise as an interference-free communications medium if combined with an electric line for power transmission. Four schemes employing radio were examined. Of these, only a system based on a transponder at each car warrants further development.

| 18. Key Words | 19. Distribution Statement |
|---|---|
| Signal transmission;<br>Power transmission;<br>Freight trains | Limited number of copies available from the Transportation Development Centre |

| 20. Security Classification (of this report) | 21. Security Classification (of this page) | 22. No of Pages | 23. Price |
|---|---|---|---|
| unclassified | unclassified | 20 | nil |

TDC CDT 79 005

## FORMULE DE DOCUMENTATION POUR RAPPORT

| 1. N° du rapport Transports Canada | 2. N° de l'étude — CDT | 3. N° de catalogue du destinataire |
|---|---|---|
| TP5703E | 6053 | |

| 4. Titre et sous-titre | 5. Date du rapport |
|---|---|
| REVIEW OF SIGNAL AND POWER TRANSMISSION TECHNOLOGY FOR FREIGHT TRAINS<br>Rapport sommaire | Juillet 1984 |
| | 6. N° du rapport de l'organisme exécutant<br>84-4 |
| 7. Auteur(s)<br>G.J.M. Aitken | 8. N° de dossier Transports Canada<br>D1465-158-6 |
| 9. Nom et adresse de l'organisme exécutant<br>Canadian Institute of Guided Ground Transport (CIGGT)<br>a/s Queen's University<br>Kingston, Ontario K7L 3N6 | 10. N° de dossier — ASC<br>11SD.T8200-3-3527 |
| | 11. N° de contrat — ASC ou Transports Canada<br>OSD83-00070 |
| 12. Nom et adresse de l'organisme parrain<br>Centre de développement des transports, Suite 2421<br>1000 Sherbrooke ouest, Montréal, Québec H3A 2R3<br>Canadian Pacific Ltd, Gare Windsor<br>Montréal, Québec H3C 3E4 | 13. Genre de rapport et période visée<br>Sommaire, août 83-juillet 84 |
| | 14. Code de l'organisme parrain<br>CDT 6053; CP 1871-Q-19 |
| 15. Remarques additionnelles<br>Sommaire de TP5704E/CIGGT 84-4, "Review of Signal and Power Transmission Technology for Freight Trains, Juillet 1984 | 16. Agent de projet — CDT<br>M. Avni |


17. Resume

Ce rapport concerne l'élaboration d'un modèle de simulation d'une ligne de transmission devant écouler les signaux de surveillance et de freinage dans le cas des trains de marchandises, et la définition des sources d'alimentation à prévoir, délimitant ainsi le cadre d'évaluation des technologies étudiées. Des systèmes de transmission faisant appel soit à des agents matériels embarqués, soit à des agents extérieurs, immatériels ont été envisagés. Il a été constaté que les lignes de transmission bifilaires classiques ont pour elles la simplicité, la robustesse et la fiabilité. C'est pourquoi la recherche a surtout porté sur le point faible des liaisons inter-wagons, c'est-à-dire les connecteurs. Aucune technologie n'a pu satisfaire pleinement à l'ensemble des prescriptions définissant un connecteur parfait. Néanmoins, certaines techniques d'interconnexion utilisées dans des domaines autres que ferroviaires ont été jugées intéressantes. Par exemple, la technologie de fibres optiques qui est insensible aux parasites électromagnétiques, mais qui doit être combinée à une ligne de transmission d'énergie électrique. Quatre technologies utilisant la propagation des ondes radio ont été examinées. Seule celle qui utilise un transpondeur à bord des wagons mériterait d'être approfondie.


| 18. Mots-clés | 19. Diffusion |
|---|---|
| Transmission de signaux. Transmission d'énergie électrique. Trains de marchandises. | Nombre limité de copies disponibles auprès Centre de développement des transports |

| 20. Classification de sécurité (de ce rapport) | 21. Classification de sécurité (de cette page) | 22. Nombre de pages | 23. Prix |
|---|---|---|---|
| non-classifié | non-classifiée | 20 | nil |

## BACKGROUND

Major improvements in freight train safety and operating efficiency could be realized if communications links existed between the locomotive cab and individual cars. Cab-car links would permit continuous monitoring of the mechanical state of the cars, on-board identification of hazardous conditions, and the electrical control of pneumatic brakes, none of which are current freight train practice.

During the 1970s, an inductively coupled connector was developed for use on freight trains. This connector meets the ruggedness and reliability criteria very well, but has too high an attenuation to be effective in a power line on long trains. The attenuation is not a problem for the transmission of communications and control signals. The limitations of the inductive connector and the idea that other technological advances in the last decade might offer a solution to the on-board communications problem led to the initiation of the present study.

## OBJECTIVE AND METHOD

The objective of the study is to identify and evaluate new technology which might be applicable to the transmission of signals and power on freight trains without the limitations imposed by the tuned inductive connector. Information was obtained through computer and manual literature searches, patent searches, consultation with manufacturers and railway users of relevant products, and consultation with personnel in agencies such as the Federal Railroad Administration, Association of American Railroads, etc.

New technology in this study includes new developments in established and obviously relevant fields, truly new fields which have come to the fore in the past decade, and developed technology whose application to freight trains is new.

## DATA AND POWER REQUIREMENTS

Since no firm information defining the on-board communications needs of a fully instrumented and controlled freight service was available, a data model for monitoring (car-to-car communications) and brake control

(cab-to-car communications) was devised. This model is not a system design but simply an attempt to establish an initial estimate of the quantity of data that must be handled, and to provide a framework for the technological assessments. Data rates of 6 kbps would be adequate to accommodate the polling of each car every 10 seconds and the updating of the brake instructions every 0.1 seconds in common-mode braking. A rate of 134 kbps is needed for the same performance if selective braking instructions are addressed to each car. Local intelligence on the cars could reduce data rates substantially and permit all functions to be accommodated in voice-bandwidth channels. Train lengths of up to 200 cars have been allowed in this study.

Power requirements for on-board microelectronic systems and communications equipment would be of the order of 1 to 2 watts, while the electromechanical systems needed for electrically controlling the pneumatic brakes would require 10 to 20 watts per car. Since the brake controller requires this level of power only when executing a change in brake condition, local storage could greatly reduce the average power required.

A fundamental question underlying any consideration of new electronic technology on freight trains is whether on-board power sources are acceptable to the railways. While power sources were not part of this study, a number of schemes intended for railway use were encountered. These include piezoelectric and accelerometer generators operated by vibration, generators operated by the air-pressure system, solar cells, thermal energy from bearings, nuclear batteries and long-life lithium cells. In all cases instantaneous power is small and local storage would be needed. Thus, it seems rechargeable batteries of some sort are inevitable (generators driven from the axle have been ruled out for economic and maintenance reasons).

If batteries and other sources are not acceptable on freight cars, then the train transmission line appears to be the only practical way to deliver power to the cars. An analytical study is presented which shows why radio-frequency and microwave power distribution are inherently inefficient, and that the transmission of power from the locomotive to the cars would best be accomplished by a two-wire transmission line at low frequencies.

The proposed data model and power requirements are compared to those of Locotrol, ETUs and the proposed European UIC standards.

## ON-BOARD TRANSMISSION MEDIA

### Transmission Lines and Connectors

Conventional two-wire transmission lines offer simplicity, ruggedness, low cost and the capability of carrying both signals and power. Set against them are (i) the need to equip all cars and (ii) the loss of the link if the continuity of the line is broken. Much of this study was devoted to the main technical uncertainty of train lines, the inter-connector.

In order to have a point of reference for assessing current connector technology as it relates to the inter-car connector problem, a set of specifications for the ideal connector were drawn up. Primary considerations were a quick-connect/pull-apart coupling mechanism, capablity to mate regardless of the orientation of the cars in the train, protection from the environment, and the ability to be left unconnected and exposed to weather for weeks at a time yet reliably make contact when reconnected. Reliability and failure rates were examined using the U.S. MIL-Spec. model. Unfortunately, none of the military environments is a close match to the railway environment. Nevertheless, some worst-case situations led to the observation that the primary causes of connector failure will most likely be damage, inappropriate treatment, lack of maintenance, and other "failure mechanisms" peculiar to the railway environment. The traditional electrical, mechanical and chemical factors contributing to connector deterioration will be secondary factors in properly designed connectors. A number of failure mechanisms found in rail and rapid transit use of connectors are discussed in the report.

Connector technology was examined under the topics: coupling mechanisms, contact technology which includes the contact materials used in recently developed connectors for harsh environments and new techniques for protecting contacts, hermaphroditic coupling techniques, electromagnetic interference, and vibration effects. Examples of interesting, relevant connector technology have been found in various AMP, Amphenol-Tuckel, Anderson, Cannon and Pyle-National connectors.

Automatic connectors of the type used on rapid transit vehicles have been examined as well.

There do not appear to be any individual connectors on the market which will satisfy all of the specifications for the ideal connector proposed. However, there are a number of clever techniques which might be incorporated in whole or in part into a new connector designed specifically for freight train application. The two technical problems which must be solved if an acceptable cable-end connector is to be realized are the provision of (i) a hermaphroditic mechanical coupling mechanism with a good environmental seal and (ii) a means of covering the contacts of at least the socket, but preferably of both the socket and plug, when disconnected.

At the moment the only interconnection systems capable of meeting the specifications using existing techniques and components are (i) jumper cables with identical connectors on both ends, and (ii) tandem or parallel cabling in which both ends of the car are outfitted with a cable and a receptacle. In both cases two connectors must be mated.

The most attractive connector scheme from the point of view of train operation is the proposed air-hose connector with integrated electrical contacts, which would permit electrical and air coupling in one operation. This suggestion is purely conceptual at this stage and would have to be developed somewhat before any conclusions could be drawn regarding its viability. However, the potential advantages of such a solution are so great that the idea should not be lightly dismissed.

The handling of damp connectors with live power lines could be a serious safety consideration. A breaker system at the head-end would have to ensure that lines were dead before connectors are handled.

Optical Fibres

A simple optical fibre link offers complete immunity from electrical interference, a propagation mechanism unaffected by its surroundings, and a bandwidth far in excess of the data needs proposed. But, because it needs both a power source on the car and an inter-car connector, the optical fibre alone is not a viable proposition. However, a hybrid

optical-electrical connector has considerable potential. The connector problems are basically the same for the optical and electrical systems. Expandable-beam-lens techniques look like the best choice for an inter-car connector. A covering mechanism is certain to be needed to protect the optical interface from dirt and damage.

Continuity of the optical system throughout the length of the train is not possible without amplification. Thus, two failure possibilities exist which can disrupt the whole link: failure of a connector and failure of an opto-electronic repeater. Parallel and loop systems can provide redundancy.

Areas needing further investigation are the reliability and long-term stability of electro-optic systems and components, and the field servicing problems raised by the relatively high level of technology involved. Terminal hardware is still developing. In the future integrated-optics can be expected to provide reliable low-cost component systems suitable for environmentally secure packaging.

The results of experimental systems for passenger transportation systems in Japan and Germany should be followed closely.

### Waveguide

Waveguides are relatively bulky, expensive, require substantial environmental protection, and are not a practical way to send quantities of power along a train. Microwave signal sources tend to be relatively expensive. An inter-car connector appears to be feasible, but would have to be developed. On the whole, waveguide does not appear to offer an advantage over lower-frequency transmission lines.

## COMMUNICATIONS THROUGH EXTERNAL MEDIA

Radio, inductive coupling to a transmission line, and radio-frequency coupling to a leaky coaxial line all offer communications between cab and car without inter-car connections, without requiring every car to be equipped, and without loss of the whole system if one on-board unit fails. All need on-board power sources.

## Radio

Radio communication is at a very advanced state of development. Integrated circuit technology has permitted the implementation of sophisticated modulation and coding schemes in small, low-power packages. A major advantage of radio is that no material medium is needed to carry the signals. Radio frequency systems require VHF or microwave transmitters, receivers and antennas. As a general rule, component costs increase with frequency.

With radio a serious problem is the stability of propagation along the train. Also, the open nature of the medium makes it susceptible to interference. Coding can ensure high immunity to interferences but cannot compensate for the occasional absence of signals. Radio systems patterned after the ETUs would be suitable for most surveillance functions. However, a higher degree of transmission reliability would have to be achieved through higher power and/or data encoding if brakes are to be controlled. Equally reliable communications in both directions between cab and car are necessary if "handshake" confirmations of the type used in Locotrol are to be included in the brake-control strategy.

## Inductive Coupling and Leaky Cables

The inductive coupling to a cable and the radio-frequency coupling to a leaxy coaxial line are based on the same principle. Signals are coupled into the transmission line at the locomotive, travel along the line which runs continuously parallel to the rails, and are coupled out at each car along the train. Car-to-cab communication is achieved in the same manner. These systems provide the advantages inherent in radio systems, but in principle can provide a more stable propagation medium in the form of the wayside transmission line. In this study information obtained from actual installations made it clear that attenuation of the signal path plus the attenuation of the line will reduce the signals to undesirably low levels or require excessively high transmitter powers. The inductive-coupling coils will have to be very close to the transmission line and this will make them vulnerable to damage and a problem in winter.

In both cases the wayside installation would have to be protected against vandalism, damage during roadbed maintenance, and climatic factors, making it an expensive proposition. Broken transmission lines would have serious consequences for the control signals. Neither of these propositions is considered to be viable for Canadian freight trains.

Transponder Link

The relaying of signals along the train by means of transponders on each car is the most interesting concept using radio propagation which has been encountered. A transponder is a receiver and transmitter, with associated electronic circuitry, which, when it receives a signal, automatically transmits a new signal. The transmission may be simply a repeat of the received data or transmission of a data stream composed in response to the received data. In the configuration presented as an illustration of the concept, two transmit/receive channels were employed, one for down-train communications, the other for up-train communications.

The transponder link requires no inter-car connection and no wayside installation. Because the transmission range would normally be one car length, the signal level of a receiver would be high with low transmitted power and the system is not likely to be greatly affected by propagation anomalies. It should be possible to use a simple antenna, amenable to rugged packaging and installation in a protected location. By designing the transmitter to have a range of several cars, some unequipped cars could be accommodated in the consist and failure of one unit would not disable the system. The propagation of electromagnetic waves in the "guide" created by cars and rails should be studied. Communications between cars and trackside stations is also possible.

The transponder link is the most interesting concept based on radio propagation and warrants further investigation and development, provided an on-board power source is accepted.

## ASSESSMENT

The technical criteria under which the various schemes have been assessed are:

(1) Power Transmission. Can the system deliver power from the locomotive to the cars in sufficient quantity to operate electronic circuits and EP brakes?

(2) Data Rate. What data rates can be transmitted?

(3) Mode of Access. Is access serial or direct? In the serial mode the signal must pass from one car to another. In the direct mode the signal is transmitted from the cab to the car, and vice versa, independently of equipment on other cars.

(4) Inter-Car Element. Does the system require a device to be connected between cars during coupling operations?

(5) Wayside Installation. Is wayside equipment necessary to facilitate communications along the train?

(6) Attenuation. The overall attenuation of the system for 200 cars. Attenuation is not an appropriate quantity for comparing all systems without also taking into account signal levels, amplification possibilities and interference levels.

(7) Hazards to Personnel. Are there inherent hazards to safety and/or health associated with the technique?

(8) Hardware complexity. Refers to hardware of the data link terminal on the car. Data processors, control circuitry and sensors are assumed to be the same in all systems.

(9) Hardware Failure. What are the consequences to the link of a failure in the equipment on an individual car?

(10) State of Development. This has been judged by noting whether the fundamental electrical and electronic elements are in regular use in other

applications, are experimental or prototype systems, or are conceptual and need to be developed.

(11) Link Security. Immunity to Interference (EMI). Is the propagation medium stable, free from disturbance by environmental factors such as climate or changes in the surroundings? Can the system maintain an adequate signal-to-noise ratio in the presence of the likely sources of electromagnetic interference (EMI)?

(12) Suitability. This category deals with the system ruggedness, resistance to mechanical shock and vibration, and sensitivity to environmental factors such as dust, dirt, dampness and corrosive industrial atmospheres. To a large extent ruggedness and environmental protection are a matter of packaging which, in turn, is often a matter of cost. It has been assumed that the electronic circuits could be adequately packaged and protected. There is certainly a great deal of experience with this aspect to be found in military equipment, missiles and the transportation fields in general. Large-scale integrated circuit implementations have proven to be able to reduce failure rates by orders of magnitude. Therefore, in considering suitability, attention has been directed toward other aspects that may pose problems in the freight train application.

(13) Cost Estimates. Cost estimates in Table 1 are intended to be indicative of the order of magnitude to be expected in implementing the systems and are not based on a detailed analysis. The estimates are based on the current cost of connectors, experience with the installation of the inductive connectors and transmission lines on the DAR gypsum train, the cost analyses in references 1.4 and 7.2, and the price ranges of ruggedized equipment such as the ETUs. These estimates refer only to link hardware.

An overview of the assessment is given in Table 1.

TABLE 1

FREIGHT TRAIN TRANSMISSION TECHNOLOGY: SUMMARY ASSESSMENT

| | 1<br>Power Transmission | 2<br>Data Rates (Mbps) | 3<br>Access Mode | 4<br>Inter-car | 5<br>Wayside Installation | 6<br>Attenuation 200 cars (dB) | 7<br>Hazards to Personnel |
|---|---|---|---|---|---|---|---|
| 1. Transmission Lines and Connectors: | | | | | | | |
| (a) Tandem | Yes | 0.1-0.5 | | 2 cables with connectors | | 5-15 | |
| (b) Single | Yes | 0.1-0.5 | Serial. Equipment needed on all cars | 1 cable with hermaphroditic connector | None | 5-15 | Possible shock hazard. Lines must be dead when connectors are disengaged |
| (c) Air-electric | Yes | 0.1-0.5 | | contacts on air-hose connector | | 5-15 (uncertain) | |
| (d) Tuned-inductive | No | 0.02-0.04 | | 1 cable with inductive connector | | 72 (24) | None |
| 2. Optical Fibres | no | 100-1000 | Serial. Equipment needed on all cars | Cable with EBL connector | None | 200 | Possibility of accidental eye damage |
| Hybrid Optical/Electric | yes | | | Cable with EBL and electric contacts | | 200 | |
| 3. Waveguide | no | 1000 | Serial. Equipment needed on all cars | Choke flange & possible waveguide | None | 10-30 | Accidental MW emissions can cause burns, eye damage |
| 4. Radio | no | 1 (UHF) regulatory problems | Direct | None | None. May be needed in difficult terrain | 87 | None |
| 5. Inductive-Coupling to Wayside Line | no | 0.1 | Direct | None | Major. Continuous transmission line | High | None |
| 6. R.F. Coupling to Leaky Coaxial Line | no | 1 (UHF) | Direct | None | Major. Continuous leaky cable | 150 | None |
| 7. Transponder link | No | 1 (UHF) | Serial. Equipment <u>not</u> needed on all cars | None | None | - | None |

| 8<br>Hardware Complexity | 9<br>Hardware Failure | 10<br>State of Development | 11<br>Link Security and Immunity to EMI | 12<br>Suitability for Freight Railway Environment | 13<br>Link Cost per Car |
|---|---|---|---|---|---|
| Simple amplifier | Connector failure: link is disrupted<br><br>Electronics failure: transmission line is continuous and unaffected | Transmission lines are highly developed<br><br>Connector techniques exist. Adaptation needed.<br><br>Hermaphroditic coupling seal and contact cover need to be developed<br><br>Conceptual only. Needs to be developed.<br><br>Prototype exists. Has been field-tested. Improvement possible. | Stable propagation independent of surroundings.<br><br>EMI immunity very good if shielded. | Transmission line in conduit is suitable<br><br>Ruggedness and environment resistance have been demonstrated<br><br>Uncertain until prototype is developed<br><br>Uncertain until concept proven<br><br>Meets ruggedness and reliability requirements | (Includes $200 for transmission line installed)<br><br>$1,400<br><br>$ 800<br><br>$ 300 (uncertain)<br><br>$ 300 |
| Opto-electronic transmitters and receivers, coupling devices | Connector failure or electronics failure: link disrupted | Technology evolving. Experimental railroad applications. Has been effective in other harsh environments. | Stable, independent of surroundings. EMI immunity excellent | Ruggedness through appropriate packaging. Connector performance uncertain. Dirt will be a problem. | $1,500 (uncertain) |
| MW generator, MW receiver, waveguide couplers | Same as for transmission lines | Hardware well developed. Inter-car connector concept needs to be tested. | Must have environmental protection. EMI immunity very good. | Not suitable | $2,000-$4,000 |
| VHF transmitter, receiver, antenna | Failure of one unit does not disrupt communications with the others | Electronics technology well developed. Railroad examples in ETUs, two-way radios | Propagation problems. Occasional signal loss possible. Susceptible to interference. | Can be suitably packaged. | $2,000-$4,000 |
| LF transmitter, receiver, coupling coils | | Electronics highly developed. Used in rapid transit. | Noisy environment. Low signal levels due to high path attenuation. Probably poor. | Vulnerable coils. Vulnerable wayside installation. | $2,000-$4,000 plus wayside inallation $20,000/km. |
| VHF transmitter, receiver, special antenna | | Electronics well developed. Used in subways, mines. | Low signal levels due to high path attenuation. EMI immunity uncertain. | Antenna with adequate gain may be cumbersome. Vulnerable wayside installation. | $2,000-$4,000 plus wayside installation $20,000/km |
| VHF or MW transmitter, receiver, simple antenna and encoding electronics | No disruption if transmitter range is greater than one car length. | Electronics similar to ETU or some ACI systems. Needs to be developed. | Signal levels high because distances short. Expected to be secure with good EMI reistance. | Can be suitably packaged. Antenna is amenable to rugged packaging. | $2,000-$4,000 |

## CONCLUSIONS

The main conclusions to be drawn from this study are:

(1) The only practical way of distributing power from the locomotive to the cars is by two-wire transmission line.

(2) A train-length transmission line is a very attractive communications link because of its simplicity and ability to carry both signals and power.

(3) Tandem cabling with receptacle and plug at both ends of the cars looks practical with modifications to existing connectors. Engagement forces should be reduced. The Pyle-National C-line is a good candidate. Laboratory and field-test information specific to the inter-car application is needed before reliability can be estimated with confidence.

(4) No truly hermaphroditic connectors have been found which meet the requirements of the inter-car connector. However, connectors developed for other applications have employed techniques which could prove valuable in a new inter-car connector design. Prospects for successfully developing an acceptable connector appear to be good. The most promising techniques need to be assessed experimentally in a real or simulated railway environment before firmer conclusions regarding the viability of an eventual connector can be drawn.

(5) An air-electric connector employing contacts in the glad-hand air-hose connector would have much to offer. There is some question as to whether a contact mechanisum can be successfully implemented.

(6) The tuned, inductive connector, despite its limitations, remains the simplest, least-expensive, inter-car connector meeting the reliability and ruggedness requirements of the railway environment.

(7) Optical fibres are of interest only if combined with an electric power line. Inter-car connector requirements are essentially the same as for

electric connectors. The main advantage of optical fibres in the freight train application is their complete immunity to electromagnetic interference. Highly reliable opto-electronic repeaters are needed on board cars. This evolving technology shows great promise, but more needs to be known about reliability, long-term stability and maintenance.

(8) Waveguides are not considered to offer any advantages not available in other systems.

(9) Radio offers cab-to-car communications without inter-car connections and without loss of the whole system if one link fails. The primary technical problem is transmission reliability in the environment of the moving train. With adequate power and EMI protection through coding, direct two-way radio could provide a viable communications link. Channel allocation, regulatory aspects and data-transmission protocols are areas needing further study. An on-board power source would be needed.

(10) Inductive coupling to a transmission line and radio frequency coupling to a leaky coaxial cable are not considered suitable for freight train applications because of the very high transmission path losses and the need for a continuous wayside transmission line.

(11) The transponder link is the most interesting concept employing a propagation medium external to the train. Inter-car connections and a wayside installation are not required. Failure of a unit or unequipped cars in the consist do not disrupt the link if the transponders have a range of several car lengths. This concept warrants further exploration provided an on-board power supply is acceptable.

## RECOMMENDATIONS

The recommendations given below can be grouped according to the source of electric power envisaged on the cars. If power sources on every car are not acceptable, as has been suggested by people in the railway industry, then items (1), (2) and (3) are pertinent. However, if the railways are willing to also consider independent, on-board sources,

then items (4) and (5) are of interest and, if implemented, would open the door to some quite attractive train communications concepts.

(1) An experimental assessment program should be undertaken to establish how well the most promising connector techniques would perform in the freight train environment. Candidate connectors for the tandem model as well as the techniques of interest to a new hermaphroditic connector should be included. Tests in real field environments as well as laboratory simulation would be valuable. A field test site already exists in the transmission line installed on the DAR captive fleet in Nova Scotia. It should be exploited for the studies of other types of connectors as well as the inductive connector currently in place.

(2) Connector manufacturers expressing an interest in the inter-car connector as a possible product line are, in alphabetical order, AMP, ITT Cannon and Pyle-National. However, they have some reservations as to whether the railways are genuinely interested in the train-line concept. Connector manufacturers should be invited to prepare prototypes for evaluation with funding, at least in part, by Transport Canada and the railways as an incentive. This recommendation does not preclude the more financially modest assessment proposed in recommendation (1) above, which would be the precursor to prototype development.

(3) The experimental programs evaluating optical-fibre links on passenger vehicles in Japan and West Germany should be monitored closely. Because coupling and protection are essentially the same for electrical and optical contacts, the studies recommended in item (1) are pertinent to the hybrid electrical-optical connector. Further information should be sought regarding the reliability of the expanded-beam-lens technique and electro-optic terminals and repeaters.

(4) The transponder link and the direct cab-to-car radio link require on-board power. Since both of these systems eliminate the constraints of (i) an inter-car coupling-up operation, and (ii) vulnerability of the system to failure of one component, they could prove more attractive than

transmission-line systems if suitable power sources were available on the cars. Therefore, a study of energy storage devices and methods of replenishing them should be undertaken immediately.

(5) The transponder link should definitely be given further consideration if an on-board power source can be accepted. The design and development of an experimental system should be undertaken in order to address concrete problems of data encoding needs and protocols, communications modes, optimum frequency, transmitter power-levels, receiver sensitivity, and packaging. An investigation of the "waveguiding structure" formed by the car body, wheels and axle, and the rails would be part of this development. Evaluation should include a relative assessment of the transponder link and direct radio links performing the same monitoring and control functions.